NASA TECHNICAL MEMORANDUM

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FLAT CONDUCTOR CABLE SYMPOSIUM, OCTOBER 10-12, 1972

By James D. Hankins (Coordinator)
Process Engineering Laboratory

December 8, 1972

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

EDITOR'S NOTE

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ERRATA

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Page iv: Paper by L. Wolf is incorrectly shown as being on page 18-1. This should be corrected to read page 19-1.

Page iv: Paper by G. Romriel entitled "Status and Availability of FCC Hardware" is not shown. The page is corrected by showing the above paper to be found on page 18-1.

TECHNICAL REPORT STANDARD TITLE PAGE

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Prepared by Process Engineering Laboratory, Science and Engineering

16. ABSTRACT

This report documents the proceedings of a Flat Conductor Cable (FCC) Symposium and Hardware Exhibit which was held at Marshall Space Flight Center during October 10, 11, and 12, 1972. A total of 24 (out of 26) papers and presentation outlines are included covering cables, connectors, termination techniques, electrical characteristics, aerospace applications, and non-aerospace applications. Questions and answers during a panel discussion are included plus a listing of vendors that displayed FCC hardware.

NOTE: This report was not edited by NASA. The compiled papers were printed from materials as provided by the participants in the symposium. Questions should be directed to the respective authors, not Marshall Space Flight Center.

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FLAT CONDUCTOR CABLE

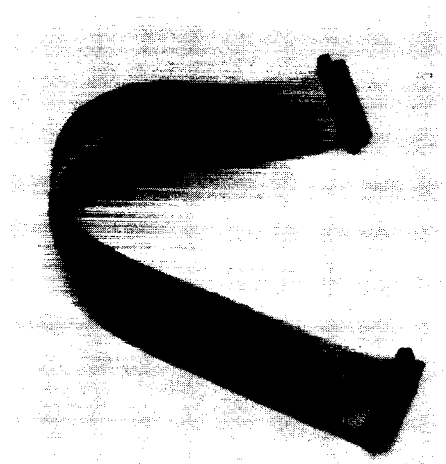
Symposium

AND

HARDWARE EXHIBIT

MORRIS AUDITORIUM
BUILDING 4200
MARSHALL SPACE FLIGHT CENTER

TUESDAY ■ WEDNESDAY ■ THURSDAY
OCTOBER 10, 11, 12, 1972



GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

TUESDAY OCTOBER 10, 1972

7:45 Bus Departs Carriage Inn for MSFC

8:15 Registration - Lobby - Building 4200 - MSFC

8:50 Building 4200 - Morris Auditorium - Tech. Meeting call to order/announcements ----------- Mr. J D Bennight, MSFC-Process Engineering Lab.

9:00 Introductions ----------- Mr. J D Bennight, MSFC-Process Engineering Lab.

9:05 Welcome ----------- Dr. William R. Lucas, MSFC Deputy Director, Technical

9:15 Purpose of Symposium ----------- Mr. James W. Wiggins, MSFC-Tech. Util. Off., Director

9:20 Why FCC ----------- Mr. Wilhelm Angele, MSFC-Research & Dev. Div., Chief

TUESDAY SESSION CHAIRMAN ----------- Mr. Robert M. Aden, NASA-MSFC-Astrionics Lab

9:30 Cable Manufacture ----------- Mr. Paul Gamble, Hughes Aircraft Co.

9:45 Cable Design ----------- Mr. B. A. Gerpheide, Hughes Aircraft Co.

10:00 Woven Cable & Harness ----------- Mr. E. A. Ross, Southern Weaving Co.

10:30 BREAK

10:50 HALAR Fluoropolymer - A Versatile Insulation Material ----------- Dr. A. B. Robertson, Allied Chemical Corp.

11:10 Thermal Characteristics Under Load ----------- Dr. Robert F. Carlton, Middle Tennessee State University

11:35 Electrical Impedance of FCC ----------- Dr. Yiu Sing Liu, John C. Calhoun State Tech. Jr. Col.

12:00 Analytical Prediction of Digital Signal Crosstalk in FCC ----------- Dr. A. P. Belle Isle, General Electric

12:25 LUNCH - Building 4200 - Cafeteria/Basement

1:20 Busses Depart Bldg. 4200 for Bldg's 4706 (Neutral Buoyancy Sys.), 4707 (Space Exper. Mockups) and 4711 (MSFC FCC Dev. Lab.)

	Group A	Group B	Group C	Group D
1:30	4711	4711	4706	4707
2:00	4711	4711	4707	4706
2:30	4706	4707	4711	4711
3:00	4707	4706	4711	4711

3:40 Busses Depart Bldg's 4706, 4707, and 4711 for Bldg. 4200

3:50 Building 4200 - Lobby - Hardware Display

5:00 Bus Departs Building 4200 for Carriage Inn or Officer's Club (Safeguard Room) for Social Hour

6:30 Bus Departs Officer's Club for Carriage Inn

WEDNESDAY OCTOBER 11, 1972

8:00	Bus Departs Carriage Inn for MSFC	
8:30	Building 4200 - Morris Auditorium - Tech. Meeting call to order/announcements	Mr. J D Bennight MSFC-Process Engineering Lab.
	WEDNESDAY AM SESSION CHAIRMAN	Mr. Vincent Caruso NASA-MSFC-Process Engr. Lab
8:40	Mfg. & Qual. Control of FCC Harnesses	Mr. W. L. Malohm/Mr. J. Vandergriff North American Rockwell
9:00	Energy Pulse Bonding	Mr. G. C. Smith Bendix Corp.
9:30	Transition Splices and Cost Comparisons	Mr. M. D. Remedios The Boeing Company
10:00	Development of a Flat Cable System	Mr. Robert M. Neel Raychem Corp.
10:30	BREAK	
10:50	Military Usage of Connectors	Mr. Richard Schade DESC
11:00	MSFC Connector Dev.	Mr. Wilhelm Angele MSFC-Research & Dev. Div., Chief
11:30	Description of Crimp Contact	Mr. Jon Wigby Burndy Corp.
12:05	Connector Interchangeability	Mr. Thomas Berilla Department of Defense
12:35	LUNCH - Building 4200 - Cafeteria/Basement	
	WEDNESDAY PM SESSION CHAIRMAN	Mr. John Knadler NASA-MSFC-Quality & Rel. Lab
1:30	C J Concept for Advanced Aircraft Wiring	Dr. Jack Redslob AMP Inc.
2:15	Advanced Wiring Tech. & Hardware Appl. - Airplane & Space Veh. Appl.	Mr. H. L. Ernst The Boeing Company
2:30	Termination of Small Electrical Components	Mr. W. F. Iceland North American Rockwell
3:00	Status & Availability of FCC Hdwr.	Mr. G. K. Romriell North American Rockwell
3:20	Building 4200 - Special Meetings**	Optional
	Hardware Exhibits	Optional
	Building 4711* MSFC FCC Dev. Lab.	Optional til 4:30
4:45	Bus Departs Building 4200 for Carriage Inn	

*Shuttle Bus round trip between 4200 and 4711 each 20 min.
**As announced

THURSDAY OCTOBER 12, 1972

8:00	Bus Departs Carriage Inn for MSFC	
8:30	Building 4200 Morris Auditorium - Tech. Meeting call to order/announcements	Mr. J D Bennight MSFC-Process Engineering Lab.
	THURSDAY SESSION CHAIRMAN	Mr. Marvin Brown NASA-MSFC-Tech. Util. Off.
8:40	Flat Conductor Cable Technology	Movie
8:55	Low Voltage FCC for Home & Business	Mr. L. Wolf Hobby Hill Inc.
9:35	FCC for Homewiring	Mr. J. Hankins NASA-MSFC
10:00	FCC for ALSEP (Lunar Experiment)	Mr. George Cripps Bendix Corp.
10:40	Cabling Designs for Phased Arrays	Mr. Irving Kruger RCA
11:00	FCC in Viking Articulated Boom	Mr. E. S. Hawkins Celesco Industries
11:20	Military & Aerospace Appl. of FCC	Miss Candace Swanson Hayes International Corp.
11:35	Panel Discussion	Mr. Robert Lindstrom, Moderator MSFC Shuttle Proj. Off., Dep. Mgr.
12:25	Adjournment of Agenda Papers	Mr. Robert Lindstrom/Mr. W. Angele NASA-MSFC
12:35	LUNCH	
1:30	Building 4200 - Special Meetings**	Optional
	Hardware Exhibits	Optional
	Building 4711* - MSFC FCC Dev. Lab.	Optional til 3:30
	Building 4707* - Space Exper. Mockups	Optional til 3:30
2:30	Bus Departs Building 4200 for Ala. Space and Rocket Center	Optional (Cost $1.50)
3:30	Symposium Officially Completed	
3:40	Bus Departs Building 4200 for Carriage Inn or Jetport	
4:30	Bus Departs Ala. Space and Rocket Center for Carriage Inn or Jetport	

*Shuttle bus round trip between 4200 and 4711/4707 each 20 minutes
**As announced

SPEAKERS AND/OR PANEL

Speakers

Leo Wolf, President
Hobby Hill, Inc.
417 North State St.
Chicago, Ill. 60610

James D. Hankins
NASA-MSFC
S&E-PE-ME
Marshall Space Flight Center,
Alabama 35812

George A. Cripps
Bendix Aerospace Systems Division
3300 Plymouth Rd.
Ann Arbor, Michigan 48107

Irving D. Kruger
RCA
Missile and Surface Radar Div.
Bldg. 101-203
Moorestown, N.J. 08057

Eugene Hawkins
Celesco Industries
3333 Harbor Blvd.
Costa Mesa, Calif. 92626

C. Swanson
Hayes International
204 Oakwood Ave. NE
Huntsville, Ala. 35801

Wm. L. Malohn
North American Rockwell Corp.
12214 Lakewood Blvd.
Downey, Calif. 90241

James Vandergriff
North American Rockwell Corp.
12214 Lakewood Blvd.
Downey, Calif. 90241

Gerald C. Smith
Bendix Elec. Comp. Div.
Sherman Ave.
Sidney, N.Y. 13838

M. D'Almada Remedios
The Boeing Co.
Mail Stop 47-18 Box 3707
Commercial Airplane Elect. Sys.
Seattle, Wash. 98124

Robert M. Neel
Raychem Corp.
300 Constitution Dr.
Menlo Park, Calif. 94025

R. Schade
DESC-EMT
Defense Elec. Supply Center
Dayton, Ohio 45444

Wilhelm Angele
NASA-MSFC
S&E-PE-M
Marshall Space Flight Center,
Ala. 35812

Jon Wigby
Burndy Corp.
Richards Ave.
Norwalk, Conn. 06852

Thomas Berilla
National Security Agency
Bldg. 3, Room S-212
Fort Meade, Md. 20755

Dr. J. J. Redslob
AMP Incorporated
Eisenhower Blvd.
P. O. Box 3608
Harrisburg, Pa. 17105

H. L. Ernst
The Boeing Co.
Mail Stop 47-18
P. O. Box 3707
Seattle, Wash. 98124

W. F. Iceland
North American Rockwell Corp.
Space Div. 41-070, Mail Code AE24
12214 Lakewood Blvd.
Downey, Calif. 90241

G. K. Romriell
North American Rockwell Corp.
Space Div. 41-153, Mail Code AA91
12214 Lakewood Blvd.
Downey, Calif. 90241

Paul Gamble
Hughes Aircraft Co.
Mail Stop C-1410
500 Superior Ave.
Newport Beach, Calif. 92663

B. A. Gerpheide
Hughes Aircraft Co.
Bldg. 6 MS (D-133)
Teale St.
Culver City, Calif. 90230

E. A. Ross
Woven Elec.
Div. of Southern Weaving
P. O. Box 189
Mauldin, S. C. 29662

Dr. A. B. Robertson
Allied Chem.
Plastics Div.
P. O. Box 2365 R, Bldg. DAB
Morristown, N. J. 07960

Dr. Robert F. Carlton
Middle Tenn. State Univ.
P. O. Box 407
Murfreesboro, Tenn. 37130

Dr. Yiu Sing Liu
John C. Calhoun State Tech. Jr. College
32 Woodside Dr., Route 7
Athens, Ala. 35611

Dr. A. P. Belle Isle
General Electric
Ordnance Sys.
100 Plastics Ave.
WCCE – Rm. 2556
Pittsfield, Mass. 01201

Panel

R. Schade
DESC-EMT
Defense Elec. Supply Center
Dayton, Ohio 45444

Wilhelm Angele
NASA-MSFC
S&E-PE-M
Marshall Space Flight Center,
Ala. 35812

Paul Gamble
Hughes Aircraft Co.
Mail Stop C-1410
500 Superior Ave.
Newport Beach, Calif. 92663

N. J. Cotter
E.I. DuPont de Nemours and Co.
Plastics Department
Chestnut Run
Wilmington, Del. 19898

Roger H. Ellis
Raychem Corporation
300 Constitution Dr.
Menlo Park, Calif. 94025

Clyde L. Hatch
Naval Ships Engr. Center
3700 East-West Highway
Hyattsville, Maryland 20782

E. Murray Chalmers
Ansley Electronics Corp.
Old Easton Road
Doylestown, Pa. 18901

Robert A. Klotz
Consultant Engineer
203 Woodland, Pinevilla
Post Falls, Idaho 83854

WHY FCC

By Wilhelm Angele
MSFC - Research & Dev. Div.

OPENING REMARKS
TO THE FLAT CONDUCTOR CABLE (FCC) SYMPOSIUM

W. Angele
Process Engineering Laboratory
NASA/MSFC

WHY FLAT CONDUCTOR CABLE?

This question has been asked many times, particularly by electrical engineers who have been using exclusively round wire cable during their professional lives. To answer, let us first apply the same question to other electronic advancements. Why do we use printed wiring boards? Why transistors? Why integrated circuits? Why not go back to the vacuum tube age, when a 10-watt amplifier for a movie theater weighed 100 pounds? In all cases, one overall, compelling reason for use of new technology stands out: the urge for progress.

Progress is everyone's business, and technical progress is the engineer's business, as the name "engineer" implies. At this symposium, FCC and the technical progress which it has brought about are our business.

HOW DOES FCC BRING TECHNICAL PROGRESS?

To answer this question we need to understand the very nature of FCC: its materials; its design and mechanical configuration; the physical, mechanical and electrical properties (such as weight, volume, temperature range, flexibility, mechanical strength, electrical load capability, repeatability of electrical behaviour in characteristic impedance and cross talk, and reliability); termination and connector systems; its installation; and last but not least - its low installed cost. A consideration of these factors, and a brief look at some of the reasons behind the use of FCC by the electronics industry in specific applications will clearly show the technical progress which can and is resulting from use of flat conductor cable.

The Nature of FCC

Summaries of design characteristics and various advantages of FCC use are given in Tables 1 - 5, accompanied by details of explanation.

TABLE 1

MECHANICAL DESIGN

1.	Harder Insulation	-	No Cold Flow
2.	Higher Insulation Strength	-	Thinner Insulation
3.	Thinner Conductors	-	More Mechanical Flexibility
4.	Better Heat Dissipation	-	Higher Load Capacity
5.	Lower Temperature	-	Higher Electrical Conductivity
6.	Volume Reduction	-	Space Saving
7.	Weight Reduction	-	Cost Saving

1 & 2. Mylar, Kapton and other insulation materials used in FCC are higher in tensile and compression strength and have better cold flow properties than materials frequently used for RWC, such as PVC, Teflon, and Silicone. These better materials allow use of thinner layers of insulation which results in more mechanical flexibility.

3. The thin rectangular geometry of the conductors also results in more mechanical flexibility.

4. Thinner insulation, more surface area and a better chance for heat sink gives higher electrical load capacity, and/or

5. Lower temperature of the conductors, therefore higher electrical conductivity.

6 & 7. Thinner insulation and less copper naturally result in volume and weight reduction, and thus savings in space and cost.

TABLE 2

ELECTRICAL DESIGN

1.	Characteristic Impedance	- Fixed by Cable Dimensions and Materials
2.	Cross Talk	- Predictable from Tables
3.	Electrical Performance	- Constant from Unit to Unit
4.	Shielding Need	- Reduced by Conductor Arrangement
5.	Shielding Efficiency	- Very High

1 & 2. Characteristic impedance and cross talk have been established by calculation and actual measurements. These data can be obtained and depended upon because the individual conductors are located in a fixed environment and have fixed dimensions with regard to each other and to the ground conditions.

3. The electrical performance is therefore constant from unit to unit.

4 & 5. The need for electrical shielding is greatly reduced; however, when used, shielding is more efficient than RWC shielding. In most cases separate shielding is not required because disturbing conductors can be physically removed from sensitive ones, or ground conductors can be placed on each side of the sensitive conductors, or the cable is mounted to grounded metal substrates. When shielding is still needed in special cases, the shield is much more effective due to thinness of the insulation and the flatness of the conductors.

TABLE 3

MANUFACTURING ADVANTAGES

Simpler Cable Design	- Production Cost Saving
Simpler Harness Mfg.	- Time Saving - Shorter Lead Time
Automatic Termination	- No Wiring Mistakes
Simpler Installation	- Time & Cost Saving
Damaged Cable	- Inexpensive to Replace

TABLE 4

INSPECTION AND RELIABILITY

Good Visibility
Simple Inspection
Simple Trouble Shooting
High Strength Insulation
Load Sharing of Conductors and Insulation
High Vibration Life
No Cold Flow Under Reasonable Stress
Fewer Electrical Junctions in Several Termination Designs

TABLE 5

COST SAVINGS

Lower Production Cost for Cable
Lower Manufacturing Cost for Harness
Lower Volume and Weight, Saves Cost
Simpler Inspection
Lower Installed Cost

Saturn IVB FCC-RWC Comparison Study

Under contract to MSFC, McDonnell Douglas converted half of the Saturn IVB aft skirt from round wire cabling to FCC. The purpose of the contract was to study the feasibility of FCC use and to produce comparative figures, for time, weight and cost for round wire and FCC cabling. The results of this study substantiate many of the advantages of FCC use noted earlier.

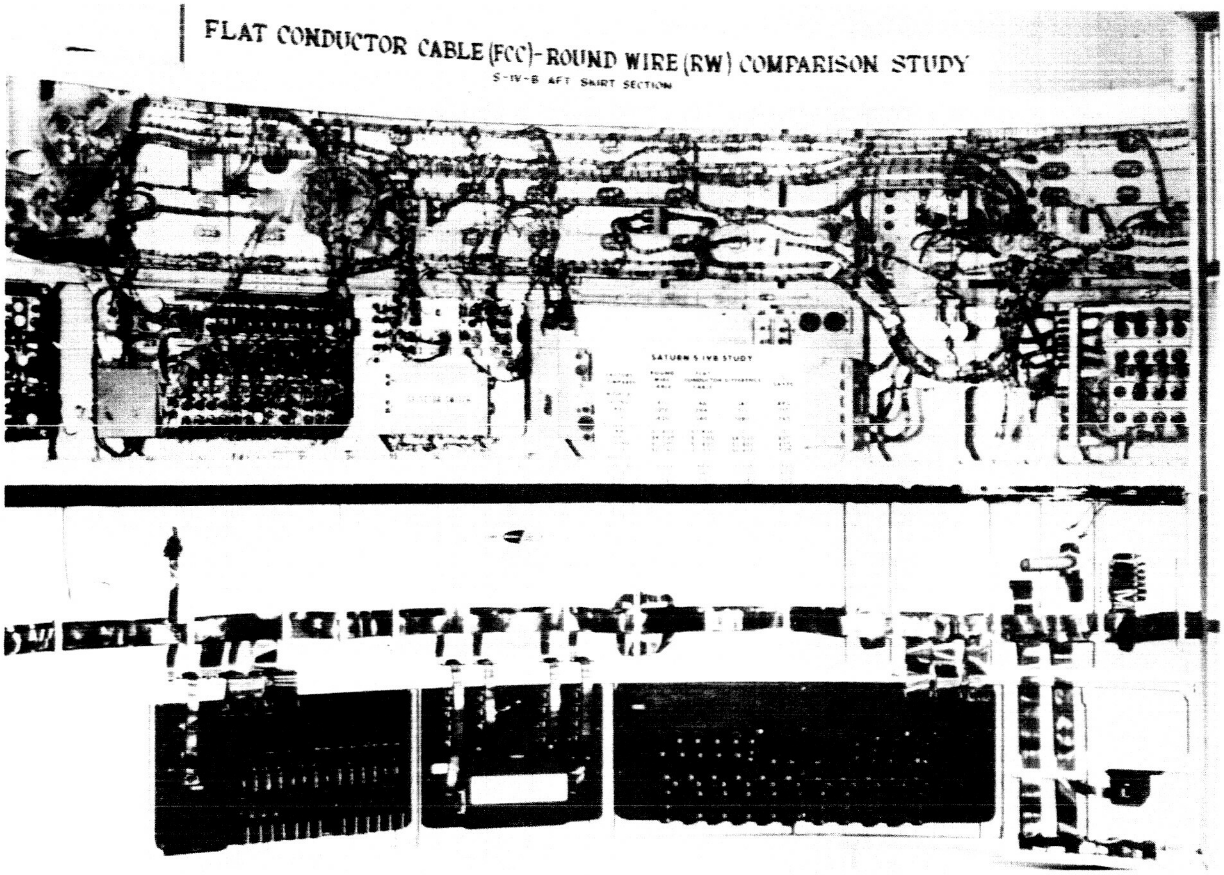


FIGURE 1. FLAT CONDUCTOR CABLE (FCC) - ROUND WIRE (RWC) COMPARISON STUDY

The upper part of Figure 1 shows the round wire cabling as it has been installed in the Saturn Space Carrier for the Apollo Program. The lower part illustrates the FCC system designed and installed to perform the functions of the round wire system above. It can easily be seen what a large difference there must be in time and space requirements between the two systems. While the round wire installation makes a confusing impression, the FCC system below appears orderly and simple, which is exactly the case. Apparently the method of round wire cable installation is left to the technician, who installs cables to the best of his knowledge, placing cables wherever he can find room, using many times more cable clamps and time as compared with the FCC installation, which is planned and designed for simplicity, cost, weight and labor savings.

TABLE 6

SATURN S-IVB STUDY

FACTORS COMPARED	ROUND WIRE CABLE	FLAT CONDUCTOR CABLE	DIFFERENCE	% SAVED
WEIGHT-LBS.				
FASTENERS	410	46	367	89%
WIRE	1010	294	713	71%
TOTAL	1420	340	1080	76%
MATERIAL COST				
WIRE	$1,430	$1,430	0	0
PLUGS	$4,730	$ 700	$4,030	85%
FASTENERS	$3,200	$ 400	$2,800	87%
TOTAL	$9,360	$2,530	$6,830	72%
MAN HOURS				
HARNESS MFG.	2,130	600	1,530	72%
INSTALLATION	1,110	360	750	67%
TOTAL	3,240	960	2,280	70%

Table 6 shows the major results of the MDAC-Saturn S-IVB cabling study in numbers. While most data are self-explanatory, some need a few comments.

Weight Reduction: At the time the study was made, about six years ago, the smallest round wire size permitted for use was AWG 24. Where electrically adequate, the FCC designer used a conductor size 4 x 40 mils, which is about a size AWG 27. This size reduction is mechanically permissable because of the strength shearing characteristic of FCC. It is not possible to stress just one conductor in an FCC. This reduction in copper gauge and insulation thickness resulted in large weight savings.

Material Cost: The table shows that the cost of RWC is equal to the cost of FCC. At the time the study was made, the cost for FCC was much higher. Now it is about equal, and in years to come, when FCC will be produced in large quantities, the price will be much lower than the price for RWC. This is based on the smaller amount of copper and insulation material required and the greatly reduced manufacturing time for FCC, as compared with RWC. Flat conductors can be made by slitting copper

foil, greatly cutting production time. For example, a copper strip 20 inches wide makes nearly 500 conductors in one pass through the slitter. Even before the slitting operation, production savings are realized because rolling the copper ingot to a 4 mil thick tape costs much less than drawing 500 round wires to a size AWG 24, which then must be individually insulated and finally hand tailored to a specific cable harness. The FCC is completely machine made and all conductors insulated to a monolithic cable in one machine passage. Therefore the cost of FCC must be much less than the cost for RWC.

<u>Man Hours:</u> FCC harness manufacturing is much less costly than with RWC. One simply cuts the desired length of FCC and terminates both ends by mechanized procedures. For a 25-conductor cable, one operation for an FCC replaces 25 operations needed for a RWC. It is my experience that the time savings in harness manufacturing is much higher than is stated in Table 6. The time savings in manually installing FCC is also higher than is stated in the table, assuming that the shop personnel have proper training and experience.

The data resulting from the S-IVB study speak a pretty convincing language, especially where the ratio of payload weight to booster weight is 1 to 20. This means that if you want to bring 1 pound of equipment into orbit it costs you 20 pounds of booster weight. In other words, FCC applied to spacecraft has an avalanche effect on savings. This makes it clear that FCCs are of special interest for the Orbiting Shuttle Spacecraft and all the many payloads for the Shuttle and other space carriers.

Reasons for Commercial Use of FCC

The advantages to be obtained from FCC use are being recognized in many commercial areas. Consider for example the automotive industry. Look under the dash board of your car - you may find FCC. Why? Because flat conductor cables are cheaper to produce and to install, and show high reliability as well.

Or note what the computer industry is doing. This industry is one of the most rapidly advancing industries, because it is progressive and produces and applies new and better technologies. The computer industry recognized very early the advantages of FCCs for signal transmission: uniformity, quality and reliability of electrical performance, and low cost.

There are other industries and areas where FCC will be used. One field deserves special mentioning: the housing industry. The producers of mobile homes and prefabricated houses, and the conventional building trade, look at FCC as a major money saving primarily because it will save labor, which is the highest part of building costs.

IN CONCLUSION: WHY FCC?

Through the past years of FCC technology development, many opportunities have come for FCC applications. These have occurred because of limited space and weight allowances, or the need for flexibility with regard to flex life for drawers, or low torque for sensitive gimbal crossings or other reasons which often dictated use of FCC. Several very pleasant surprises such as better reliability and reduction in manufacturing time were experienced during these applications. The advantages of FCC use in numerous projects have been obvious.

Why FCC? Because its use has repeatedly resulted in improved mechanical and electrical equipment performance, and has brought about substantial savings in weight, volume and cost.

During this 3-day Symposium, we will make a special effort to show and demonstrate the present status of FCC technology, and hope you will be able to introduce and increase the use of FCC in your field of activity... for the sake of progress.

CABLE MANUFACTURE

By Paul Gamble
Hughes Aircraft Company

INTRODUCTION

Flat electrical cable has been an item of interest and commercial reality for almost 100 years. A summary of the patents involved in this product would literally take many close typed pages to present and a great deal of time to study and assimilate. These many inventions not only indicate the great interest that science and industry has in the product. To be an invention, an article or process must constitute a solution to a problem in contrast to merely stating the problem. Also, it should not be covered in the prior state of the art and usually has a definite beneficial result such as increased sales, improved operations, and lower cost. If many problems were solved, then many problems existed and since many more patents are being issued yearly, not all of the problems have been solved. The commercial benefits of the inventions have been demonstrated in a multi-million dollar industry with continuing entry of industrial investment and military application.

SUMMARY

The intent of this paper is to present a survey of flat electrical cable manufacturing, particularly referring to patented processes. The economics of manufacture based on an analysis of material and operating costs has been considered for the various methods. Although this cannot be regarded as a comprehensive study of the industry, it is intended to give some attention on the competitive advantages of the several processes and discuss the products which result. The historical area of flat cable manufacture is presented to give a frame of reference for the investigation.

In 1881, W. Powell Ware received a patent for a specific telegraph cable in which the several conductors were parallel at a proper distance from each other between two sheets or strips of fabric. India rubber, gutta perch or other materials were used as adhesive. Also, a thin sheet of metal incorporated in the envelope was found to lessen the inductive effect, especially with telephone lines. Thomas Mayall in March of 1881 described a flat parallel electrical conductor cable made with unvulcanized rubber along the wires and vulcanized outer insulation. The result was a reduction in wire corrosion. In 1884 Charles Temple Jackson, who might be called the originator of flat conductor cable received a patent for a cable made with flat copper conductors, paper insulation and an adhesive backing. That same sort of cable is still a commercial reality today, flat copper, paper and all. Finally, in ancient history, Upton Balslay received a patent in 1889 for a woven electrical cable with the insulated conductors preferably twisted in pairs so that each pair constitutes a warp. The weft was a cord insulator and the entire construction formed a multiple conductor flat fabric.

The inventiveness of these far-sighted pioneers did not reach a volume market because of limited application of electrical cables, followed by an extended economic depression. However, in the 1940's with the resurgence of industry and the need for better electrical signal and power transmission, the field became active again. C. W. Abbott in 1944 brought in modern thermoplastics and oil-heated rolls to make cables with a fluted or corrugated contour insulation over the parallel wires in flat form. The plastics referred to are Vinylite[2] types although provision for other plastic insulations are covered. In addition to a contoured insulation, Mr. Abbott provided a means of perforating between conductors to allow ready access to individual lines for termination.

The advent of the printed circuit boards and miniature electronic components provided a need for these cables in the burgeoning computer industry. The forerunner in this use was the military and NASA with funds for research and development to match this need for a light, flexible cable. Wilhelm Angele[6] was the moving force in the 1950's and still is. Public communications found a volume application in central office telephone switching as reported by Bohannon[7] in 1962.

The machinery he described was quite sophisticated in having individual torque controlling motors for each wire unwind. Also, the problem of wandering conductors was partially solved by a unique guide roll system and separated rolls to first locate and then cover wires. The straightness of the wire was improved by Richter's patent[8] which utilized an integral stretching process. The need for faster cables was met by Stearn[9]. Of course, the need for high temperature, low dielectric constant cable was met by the Gore[10] sintered Teflon process in 1963. Overseas the Japanese had developed a very sophisticated process during the 1950's and made high precision cables as reported by T. Yoshida[11] of Sumitomo Electric. All of these publications reflect work begun in the late 1940's and 1950's. More recent descriptions of flat cable manufacturing methods have been much too numerous to cite here, although some have been listed in the bibiography.

Body

An analysis of the patents, publications, and trade discussions which supply comparative information on flat cable manufacturing methods shows these economic factors:

1. Efficiency of manufacture, costs.

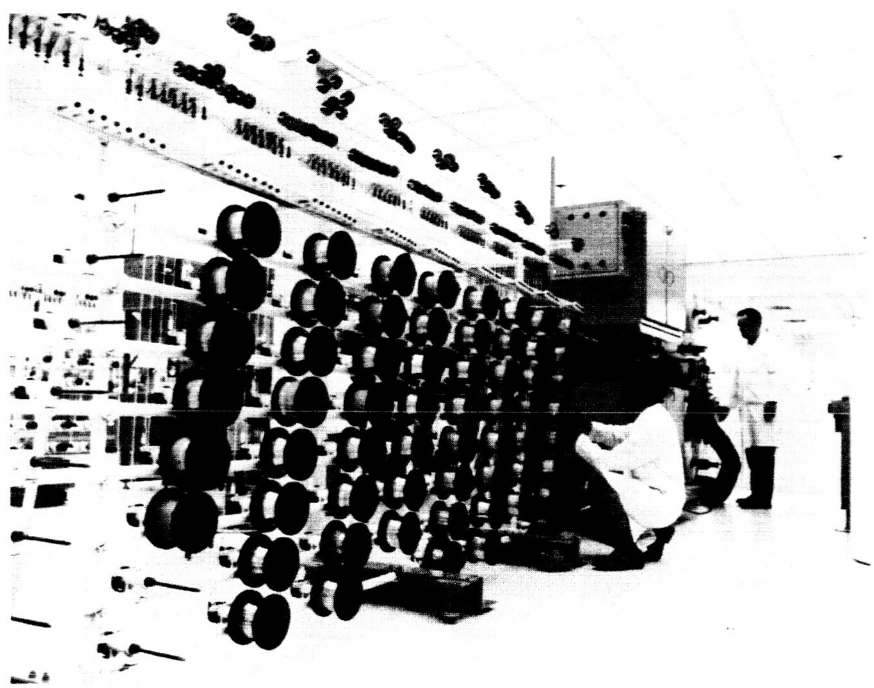
2. Flexibility of design.

3. Speed and volume of output.

4. Maintenance, durability.

5. Control.

These are not ranked in sequence of values, but in practical importance to the cable maker. Having shown a historical basis and the patent sources, we can now present some comparison on the equipment and raw materials affecting the economic parameters of flat cable production. One source[12] cites 12 companies making cable by lamination or collating methods, four by pre-insulating and laminating, two by weaving, four by etching and laminating, two by etching and spray coating, and two by extrusion. These numbers themselves say something about the economics of the processes, although they may change readily to accommodate the demand.

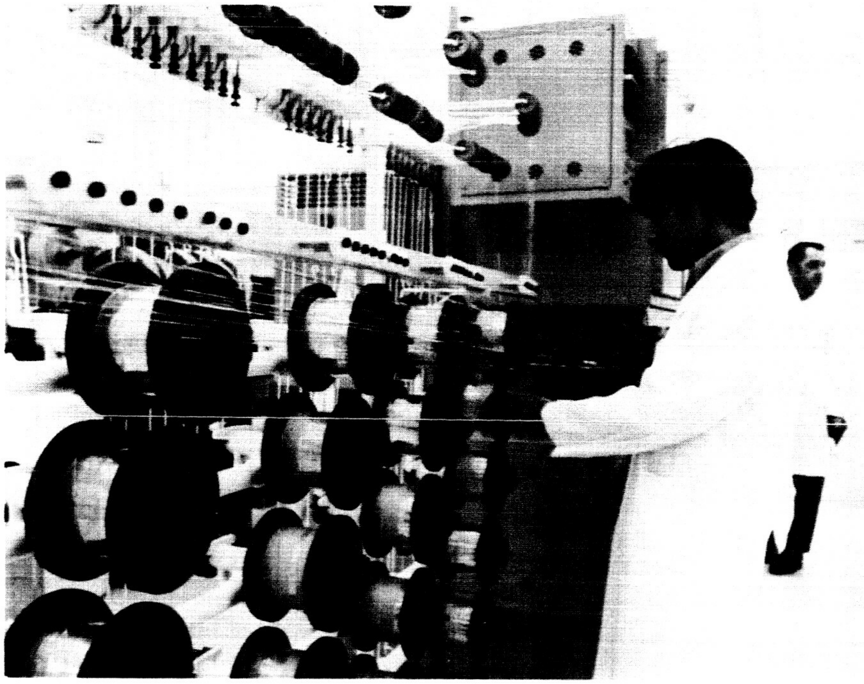


"AUTOMATIC WIRE TENSIONING EQUIPMENT"

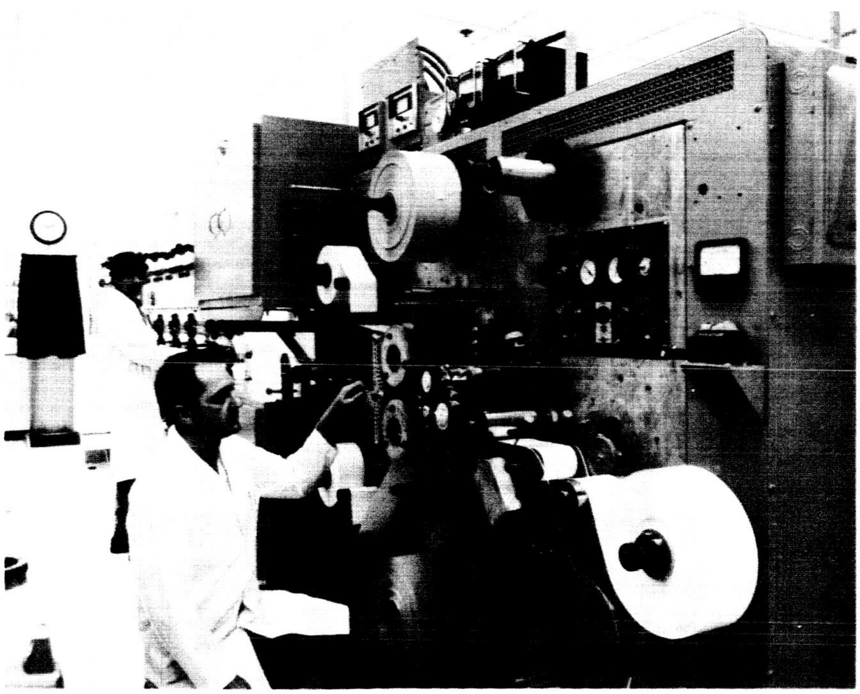
Equipment costs for the basic processes vary with the amount of specialized controls utilized. A common denominator of all processes is an unwind system for the conductors. This may vary from simple 5/8-inch rod supports for standard flat or round wire spools to flat "pancake" wind spools with individual torque motors and servotension adjustments.

The cost to purchase or fabricate this equipment will vary proportionally from about $5 per spool to about $30 per spool support. Between the two extremes of hand-adjusted spring washer brakes and auto-adjusting motors are disk brakes with air adjustment, mechanical clutches, and magnetic and inductible electric clutches with individual and cascade controls. One individual difference in the woven cable typified by the Rask patent[13] is that the conductor unwind may be of the "beam" type characteristic of the weaving industry. The advantage of this procedure is evident in an analysis of machine down-time and cable rejects. By winding a "beam," all of the conductors are changed at the same time, reducing cable rejects resulting from discontinuous conductors or knots in proportion to the number of conductors. The alternatives for individual spooling are to change all spools at the same time or to provide sufficient wire per spool to complete the production run. The down-time for spool changes may vary with the individual process from a 5 minute "flying splice" where duplicate spools are mounted on a stand to a sequenced individual wire tie-in with a one minute loss per wire. As an extrapolation to absurdity in a 100-conductor cable running at 10 ppm this would mean a loss of about 1000 feet of cable; at a nominal cost of $.02 per conductor foot, $2000.

Web unwind systems are similarly varied in design and cost. Ribbon unwinds with individual torque taper clutches are available on the market specifically designed for plastic materials. Sources are listed in the Plastics Encyclopedia. The length of the continuous unspliced insulation defines a measure of manufacturing efficiency. Low tensile strength of Teflon or polyethylene at the fusing temperature required fractional inch-ounce unwind torque from the insulation roll. This critical material can be handled with metal carrier films or continuous belts[14] as described by Marcell which may be made of blotting paper. However, they also may be of stainless steel or high temperature reinforced material. The cost of a mechanical clutch system with no sensing or control devices may be less than $25 per unwind roll. The use of tension sensing devices adds $250, control servosystems adds another $200 whether electrical or pneumatic, and these imply the use of more delicate eddy current clutches at about $30 more each. For multilaminar and shielded cables, six to eight webs will be fed into a laminating type machine.



WIRE UNWIND SYSTEMS



COLLATED CABLE LAMINATING MACHINE

Extrusion systems are singular in avoiding the convertor costs as well as web handling. Spray cover-coated cables also have less need for web unwind equipment. However, both of these require other additional material-handling devices.

CABLE ETCHING EQUIPMENT

The liquid-handling systems utilize material-handling techniques developed in the chemical processing industries; pumps valve, gages, and tanks. These being standard competitive items are relatively low cost and readily available.

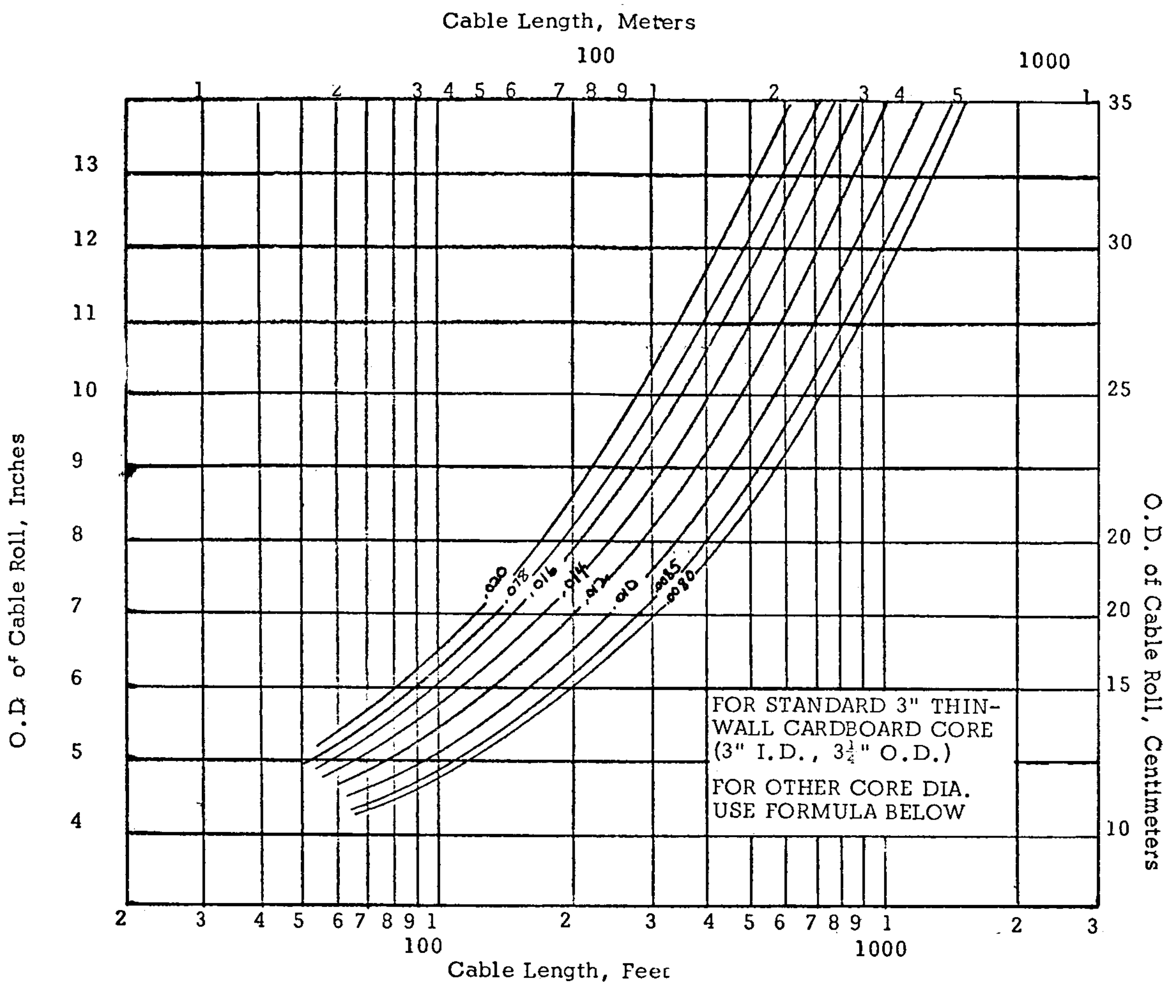
Extrusion material handling depends on the type of extrusion and the material. For example, teflon TFE may be processed from powder using a liquid hydrocarbon lubricant. The process could require liquid handling and metering equipment, slurry mixers and a preform ram press where pressures formed to a ribbon web for compaction and sintering at about 700° F. The reduction ratio in this ribbon extrusion stretches and orients the resin particles to provide physical strength for shaping and compaction about the wires in a cable. Capital cost of this material handling and processing equipment could be in the range of $100 000. Where polyolefins, chlorinated fluorocarbons, and vinyls are extruded, the unused extrusion trim may be recycled

to provide economy in raw material usage. This is also possible with FEP teflon insulation, but not as readily with TFE "Teflon." The plant design for extrusion systems will usually be quite different from the laminating, etching, or weaving plant. To utilize gravity flow for raw materials, extrusion plants customarily have a second floor or mezzanine on which compounding or preblending and mixing takes place. Granular raw material and recycled trim or scrap material may be air-veyed to elevated storage for metering into the extruder hopper. A factor in the choice of plastic to be used is also the capability of the manufacturer to utilize the raw materials efficiently. Material handling and storage are always to be minimized. Laminating production is usually in lower, light construction, warehouse type buildings. But, because of the small size and low power demands of the equipment, lamination may be done in almost any structure or part of a building used for manufacturing. Because of the inherent dust-free cleanliness, ease of handling and storage, lamination raw materials do not require special equipment except for slitting (Fig. 1).

Flexibility of operation and low conversion cost does not in itself define the best method of cable manufacture. Perhaps the least expensive and most adaptable method of production is by simple lamination or collating. However, the use of film rather than granular raw material makes this expensive. For example: the estimated teflon computer transmission line usage in the United States in 1972 will be about 36×10^6 feet increasing to possibly 60×10^6 by 1976. One 2-1/2-inch extruder with an output of 100 lb/hour could produce 30×10^6 feet of 1-inch-wide FEP teflon cable 0.030 inch thick in a year. The 1971 existing non-captive market is about 12×10^6 feet of such cable. Table 1 compares the conversion cost and Table 2 shows the approximate mill cost of three different approaches to making the same sort of cable with teflon. Assuming inspection, packaging, and shipping costs for the product to be similar, there is an advantage for the flat cable manufacturer to work with basic rather than converted raw materials.

Of course, the implication that equipment should be utilized to its fullest capacity to achieve the best efficiency should not be ignored. Unfortunately, half-million-foot orders for cable are the rarity and hundred-foot orders are not. Therefore, the product mix will consist of a few large and hopefully many small orders. The small orders may require the entire gamut of materials for insulation. Startup, tune-in, and cleanup for a small order may use as much material as for a large one.

An equation has been designed to assist in determining the proper size of the work force in relation to the total demand and the fluctuations of short runs. The method may be applied to any production operation which has



FORMULA FOR LENGTH OF FLAT CABLE IN A ROLL

L= Cable length in feet or meters
T=Cable thickness in inches or millimeters
D_i=Outside diameter of core in inches or centimeters
D_o=Outside diameter of cable roll in inches or centimeters

FOR DIMENSIONS IN INCHES AND FEET, $L = \pi (D_o^2 - D_i^2)/48T$ Feet

FOR METRIC DIMENSIONS, $L = \pi (D_o^2 - D_i^2)/40T$

FIGURE 1. LENGTH OF FLAT CABLE IN A ROLL.

TABLE 1. MANUFACTURING SIMILAR TRANSMISSION LINES.

Operating Costs	FEP Extrusion	FEP Lamination	TFE Extrusion
Installed cost per line ($M)	150 to 200	50 to 100	200 to 300
Yearly Depreciation (10%)	15 to 20	5 to 10	20 to 300
Space Required (M sq. ft)	1	0.5	5
Cost of space ($20/ft^2)	20	10	100
Yearly Depreciation (5%)	1	0.5	5
Fixed Asset depreciation allowance ($M)	11 to 21	5.5 to 10.5	25 to 35
Personnel cost per year ($M)	20	30	50
Machine operating costs ($/hr)	8	5	10
Operating speed possible (ft/min)	100 to 200	10 to 50	50 to 100
Summarized mfg. cost at 6000 (hr/year)	24 hour, 5 day week, 50 weeks.		
Personnel	20	30	50
Machine operation	48	30	60
Cost of operation	68	60	110
Depreciation costs	15	8	30
Variable overhead	10	10	10
Maximum conversion cost ($M/yr)	93	78	150
Conversion cost ($/hr)	11.1	9.3	17.8

TABLE 2. PROCESS COST COMPARISON 1-INCH CABLE 0.030-INCH THICK 10 FT/MIN

Material Method	FEP Extrusion	FEP Lamination	TFE Extrusion
Resin cost ($/lb)	6	12	4
Compounding losses ($/lb)	0.3	0	1.5
Useable compound ($/lb)	6.3	12	5.5
Resin cost $/ft of cable	0.181	0.345	0.158
Wire cost $/foot	0.04	0.04	0.04
Conversion cost $/foot of cable	0.02	0.015	0.032
Mill Cost $/foot of cable	0.240	0.40	0.230

fluctuation on the input proportions while the output proportions are to be held as nearly constant as possible. Express all work (feet of cable, assemblies, etc.) in terms of man-hours as a common unit.

F = work flow, as work units per day in and out (manhours/day)

W = work in progress, days $\times$ manhours/day (manhours)

H = holdup in work - W/F days

pi = short term projects as portion of total work load fed <u>in</u> (manhours/manhours)

po = short term projects as portion of total work load fed <u>out</u> (manhours/manhours)

$\bar{p}$ = average proportion of short term projects in progress

b = maximum deviation of pi from $\bar{p}$ or $(pi - \bar{p})/\bar{p}$ max.

c = cycle time in days, based on preceding production records

t = days (time)

Equating work input less output to accumulation yields the following:

$$piFdt - poFdt = d(poW) = Wdpo$$

and assuming a sinusoidal variation of pi. Then

$$pi = \bar{p}\,(1 + b \sin 2\pi t/c)$$

substituting holdup time for W/F and rearranging

$$\frac{d\,op}{d\,t} + \frac{po}{H} = \frac{\bar{p}}{H} + \frac{\bar{p}\,b}{H} \sin 2\pi t/c$$

by multiplying by the integrating factor $e^{t/H}$, the purpose being to make d po/d t approach zero. The left side may be integrated

$$po\, e^{t/H} = \bar{p}\, e^{t/H} + \frac{\bar{p}b}{H} \frac{e^{t/H}}{[1/H^2\ (2\pi/c)^2]} \left(\frac{1}{H} \sin \frac{2\pi t}{C} - \frac{2\pi}{C} \cos \frac{2\pi t}{C}\right)$$

with the constant of integration being zero at steady state. This equation is then rearranged to represent the variation in the ratio of short run products in the output flow of work divided by the maximum input ratio variation:

$$\frac{po - \bar{p}}{b\,\bar{p}} = \left[\frac{1}{4(H/C)\,\pi^2 + (1/HC)}\right]\left(\frac{1}{HC} \sin \frac{2\pi t}{C} - \frac{2\pi}{C} \cos \frac{2\pi t}{C}\right)$$

The value of po - $\bar{p}$/ b $\bar{p}$ should be plotted for several values of H/C (ratio of holdup time to cycle variations). The maximum value of po - $\bar{p}$/ b $\bar{p}$ is the ratio of the maximum outflow ratio variation to the maximum input ratio variation and is equal to (1 - E) one minus the efficiency of the plant.

A workshop on Printed Circuit techniques has been presented by the Rogers Corporation. The hardware, materials and sources for flexible circuit have been summarized recently in Circuits Manufacturing and other magazines.[15] With the development of sophisticated step and repeat photography, the flexible circuit flat cable has achieved some engineering objectives which were otherwise only available in ribbon cable.[16] Most of the insulations used in flat flexible cable have been described in the Directory/Encyclopedia issue of Insulation/Circuits[17] and a more thorough assessment based on recent patents was presented in "Wire Coatings" by D. J. DeRenzo[18] and excellent short courses on the subject have been presented by the E.I.C.

William Richter, the retired father of Tape Cable, was asked what characteristics he would consider in selecting insulations for flat cable, in addition to cost. He indicated the temperature rating, flame retardancy, the electrical properties and specifically dielectric constant as related to the final application of the cable. The flexibility and retractability of the cable would have a definite effect on the selection of the insulations. Taking the physical properties of the insulation, the specific gravity may have a deciding effect, in that the comparison of cost should not be based on dollars per pound, but rather dollars per square foot per mil, when the thickness of insulation is related in mils. In most flat cable applications, dielectric strength is not a

major consideration. However, the dielectric constant, because it determines the velocity of signal propagation and to some extent the thickness of insulation required on the cable, does have a definite bearing on the insulation selected. The Institute of Printed Circuits recently proposed a standard IPC-FC-231 on flexible dielectrics for use in flexible printed wiring. They included polyvinyl chloride, polyvinyl fluoride, polyethylene terephthalate, polychlorofluro-ethylene, polyethylene proplylene fluorinated, polytetrafluoroethylene, polymide, polyamide (aromatic), polyamide/imide, epoxy and other. Among the physical properties which are considered, the tear strength, the tensile strength, the shear strength and elongation have been listed, although these have practically no consideration in the selection of insulations for flat cable. Some of the materials which are listed in the accompanying table have been applied to flat cable construction but have not yet been widely accepted. These products were selected because in each case they have excellent flame resistance and adequate strip-ability, two properties which are of serious concern to flat cable users.

Although the prices of these products have not been included, the yield in square inches per pound per mil of insulation indicates the relative quantities of these materials which would be required for equivalent insulating value. This is especially true at the high frequency where vinylidene fluoride begins to approximate the dielectric constant of the other materials for transmission line use, or, in the situation where signals or power are the major requirement of the cable, the dielectric constant would not be a critical factor so these materials would compare favorably with each other.

In summation, it might be said that the method of manufacture, the general physical properties of the insulation in terms of tensile strength and so forth, should not be the primary concern of the engineer who is designing the flat conductor cable. However, depending on the process which is used, a very significant difference in the cost of the cable may result because of the differences in the price of raw materials. The designer is not limited to a single insulation in order to obtain the type of flame retardant cable or high temperature operation which may be required in modern computer applications. Therefore, I would recommend that the specific electrical properties which are needed be carefully spelled out and the choice of materials and method of production be left entirely in the hands of the flat cable manufacturer so that the least expensive cable may be obtained to perform the required function. New methods and new raw materials are continually brought on to the market and a flat cable user should be ready to avail himself of the economics and improved performance which can be obtained through their use, without restricting the manufacturer unnecessarily.

TABLE 3. LIMITED USE INSULATIONS

Trade Name	Kynar	Aclar	Lexan	Tedlar
Company	Pennwalt	Allied	GE	Dupont Riegel
Material	Vinylidene fluoride	Fluoro-halocarbon	Polycarbonate	Coated Heat Reactive
Density, gm/cu em	1.7	2.1	1.2	1.53
Flammability	Self-extinguishing	None	Self-extinguishing	Very Slow
Temperature Limit	-80° to 300°F	360°F	-200° + 280°F	300°F
Dielectric Constant	8.4 to 3	2.8	2.9	8.5
Dissipation Factor	0.05 0.02 0.16	0.008 0.01 0.03	0.05 0.1	
Notch Sensitivity	Excellent	Excellent	Excellent	Very High
Cross-Linkability			No	
Strippability	Good	Good	Good	Good
Abrasion Resistance	Excellent	Very Good	Very Good	Best
Yield, sq. in/lb/mil	16 000	13 000	22 000	17 200
Moisture Transmission, gm/mil/100 in., 2/24 hr	0.02	0.025		0.05

TABLE 4. NEW INSULATIONS

Trade Name	Tefzel	XP	GORE-TEX	XLPE
Company	Dupont	Allied	W. L. Gore Assoc.	USI Chemicals
Material	ETFE Fluoro-polymer	Fluoro-halocarbon	Foamed TFE	Flameproof Polyethylene
Density, gm/mi.^{3}	1.70	1.7	.05 to 2.2	1.8
Flammability	Self-extinguishing	Self-extinguishing	None	Self-extinguishing
Temperature Limit	150° to 300°F	-100° to 450°F	-350° to 500°F	300°F
Dielectric Constant	2.6	2.5	2	2
Dissipation Factor	$10^2 H_2$ ·0006	0.0005	-----------	0.006
	$10^3 H_2$ ·0008	------	-----------	0.006
	$10^6 H_2$ ·005	------	-----------	
Notch Sensitivity	60% Pass	Good	Excellent	
Cross-Linkability	Yes	Yes	No	Yes
Strippability	Yes	Good	Yes	Good
Abrasion Resistance	Good	Good	Good	Moderate
Yield, in.^{2}/lb/mil	16 000	16 000	290 000	15 000
Moisture Transmission, gm/mil/100 in., 2/24 hr	------	------		

FLAT CABLE PATENT SUMMARY

Number	Inventor	Date	Title
243,180	W.P. Ware	June 12, 1881	Telegraph Cable
286,035	T.J. Mayall	October 2, 1883	Insulation of Wire for Telegraph Lines
303,235	C.T. Jackson	August 19, 1884	Electrical Conductor
417,402	U.H. Balsley	December 17, 1889	Electrical Conductor
2,361,374	C.W. Abbott	October 31, 1944	Insulated Conductor Construction
2,370,846	G. Deakin	March 6, 1945	Ribbon Cable for Terminal Banks
2,731,068	K.F. Richards	January 17, 1956	TFE Polymer Bonded Heat - Resistant Fabric
2,857,450	B.M. Oliver	October 21, 1958	Transposed Conductor
2,916,055	R.E. Brumback	December 8, 1959	Extruded Tubing Sheath
2,939,905	E.L. Canfield	June 7, 1960	Electrical Conductors Connections and Methods
2,963,535	H.W. Wegener	December 6, 1960	Shielded Printed Circuit Electrical Component
2,964,587	O.N. Minot	December 13, 1960	Tape Conductor
3,004,229	T.H. Stearns	October 10, 1961	High Frequency Transmission Lines
3,029,303	J. Severino	April 10, 1962	Adhesively Secured Electrical Devices
3,057,952	G.F. Gordon	October 9, 1962	Multi-Ply Flexible Wiring Unit
3,079,458	L. Hedstrom	February 26, 1963	Flexible Tape Conductors
3,082,292	R.W. Gore	March 19, 1963	Multi Conductor Wiring Strip
3,086,071	D.S. Preston	April 16, 1963	Flexible Electrical Cable and Method of Making
3,107,197	S.J. Stein	October 15, 1963	Method of Bonding Metal to Plastic and Article
3,132,204	L.W. Giellerup	May 5, 1964	Electrically Conductive Pressure Sensitive Tape

Number	Inventor	Date	Title
3,168,617	H.W. Richter	February 2, 1965	Electric Cables and Method of Making
3,179,904	R.C. Paulsen	April 20, 1965	Flexible Multiconductor Transmission Line Etc.
3,215,574	R.W. Korb	November 2, 1965	Method of Making Thin Flexible Plastic Sealed P.C.S.
3,239,916	E.L. Love	March 15, 1966	Ribbon Cable (Pre-Stripping)
3,268,846	G.H. Morey	August 23, 1966	Heating Tape
3,296,365	R.F. Basile	January 3, 1967	Flat Conductor Cable Jumper
3,300,572	V.F. Dahlgren	January 24, 1967	Retractible Flexible Electrical Circuit Cable
3,327,077	R.W. Morris	June 20, 1967	Ribbon Cable and Switch Improvements Etc.
3,391,246	J.H. Freeman	July 2, 1968	Multi Conductor Flat Cables
3,393,268	J. Meyer	July 16, 1968	Insulated Electrical Conductors and Method Etc.
3,415,096	L.M. Griswold	December 10, 1968	Apparatus for Producing Ribbon Type Cables
3,444,506	A.D. Wedekind	May 13, 1969	Connector (3M)
3,447,120	S. Rask	May 27, 1969	Woven High-Frequency Transmission Line
3,447,122	E. Beck	May 27, 1969	Connector for Electrical Conductors
3,448,346	J.E. Webb	June 3, 1968	Extensible Cable Support
3,448,431	C. Adrien	June 3, 1969	Contact Carrier Strip
3,459,879	B.A. Gerpheide	August 5, 1969	Flexible Multi Flat Conductor Characteristic Impedance Cable
3,459,880	J.A. Erdle	August 5, 1969	Flexible Bus Bar
3,461,221	P.J. Herb	August 12, 1969	Electrical Connector for Flat Cable
3,462,542	H.W. Richter	August 19, 1969	Flat Shielded Cable Termination and Structure
3,465,435	J.J. Steranko	September 9, 1969	Method of Forming Multilayer Circuitry
3,465,432	D.J. Crimmins	September 9, 1969	Method for Making Memory Storage Units

Number	Inventor	Date	Title
3,469,016	V.E. Shelton	September 23, 1969	Interconnection Between Shield and Conductor
3,469,312	F.J.C. Leyssens	September 30, 1969	Manufacturing Multi Contact Plug-In Connectors
3,471,348	J.M. Shaheen	October 7, 1969	Flexible Circuit Connections to Multilayer Boards
3,474,188	L.R. Travis	October 21, 1969	Takeup Mechanism for Flat Electrical Cable
3,476,870	E.A. Ross	November 4, 1969	Resilient Foldable Woven Electrical Cable
3,477,059	J.E.G. Cole	November 4, 1969	Connectors for Laminar Electrical Cables
3,481,802	G.V. Marcell	December 2, 1969	Preparing Multi Conductor Cable and Flat Conductors
3,495,025	E.A. Ross	February 10, 1970	Woven Electrical Cable Structure & Method Etc.
3,499,098	B.H. McGahey	March 3, 1970	Interconnecting Matrix Conductors & Method
3,499,816	C.O. Areskoug	March 10, 1970	Enclosing Resistance Wire Tape Between Insulations
3,504,105	G. Bogner	March 31, 1970	Multi Conductor Tape with Super Conductor Metal
3,508,187	D.J. Crimmins	April 21, 1970	Inter Connection System for Circuit Boards
3,511,680	G.V. Marcell	May 12, 1970	Edge Coating of Flat Wires
3,511,728	J.H. Freedman	May 12, 1970	Making Flat Electrical Cables
3,522,484	J.W. Clemenis	August 4, 1970	Electrical Connector
3,522,652	H. Gordon	August 4, 1970	Electrical Circuit Assembly
3,523,844	D.J. Crimmins	August 11, 1970	Making Flexible Multi Conductor Flat Cable
3,524,921	L. Wolf	August 18, 1970	Two-Lead Strip Cable and Connector

Number	Inventor	Date	Title
3,527,933	H. Thummel	September 8, 1970	Flat Electrical Connecting Element
3,528,174	D.E. Harrison	September 15, 1970	Cable Termination Process
3,529,074	T.H. Lewis	September 15, 1970	External Bus Bar System
3,529,117	B.J. Costello	September 15, 1970	Soldering Apparatus (Argus)
3,533,049	J.F. Thompson	October 6, 1970	Strip Cable Connector
3,537,927	R.W. Anderson	November 3, 1970	Bonding Insulated Wires to Form Cables (HAVEG)
3,539,967	J.W. Clements	November 10, 1970	Electrical Connector (FLEXICON)
3,540,956	H.W. Arnold	November 17, 1970	Precise Conductor Cables (Gore)
3,547,718	H. Gordon	December 15, 1970	Making Flat Flexible Electrical Cables
3,550,066	H.E. Cootes	December 22, 1970	Connector for Multiple Conductor Cables (AMP)
3,576,723	W. Angele	April 27, 1971	Making Shielded Flat Cable (NASA)
3,576,941	D.F. Colglazier	January 19, 1971	Flat Power - Distribution Cable
3,555,964	L.T. Fleming	January 19, 1971	Insulation Stripping Device
3,553,836	J.E. Cootes	January 12, 1971	Method and Apparatus for Terminating Cable (AMP-VNYT)

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9. Stearns, T. H.: High Frequency Transmission Line. 3,004,229, 1961.

10. Gore, R. W.: Multi-Conductor Wiring Strip. 3,082,292, 1963.

11. Yoshida, T., et al.: Semiflat Cable. Sumitomo Electric Ind., Osaka, Japan, 1965.

12. Proposed Military Standardization Handbook MIL-HDBK-Guidance for Flexible Flat Multi-Conductor Cable. Project Number 6145-0574, Table 2-1.

13. Rask, S. et al.: Woven High Frequency Transmission Line. 3,447,120, 1969.

14. Marcell, G.V.: Method and Apparatus For Preparing Multi-Conductor Cable With Flat Conductors. 3,481,802, 1969.

15. Insulations/Circuits. vol. 17, no. 9, Circuit Processing Roundup, August 1971, p. 14.

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17. Sect. B-10 and B-11 Directory/Encyclopedia Issue, Insulation/Circuits. vol. 17, no. 7, June-July 1972.

18. Di Remo, D. J.: Wire Coatings. Noyes Data Corp., Noyes Bldg., Park Ridge, New Jersey, 1971.

CABLE DESIGN

By B. A. Gerpheide
Hughes Aircraft Company

SUMMARY

The importance of material selection is stressed in the design and manufacture of Flat Conductor Cable. Several applications of flat conductor cable are discussed relative to material selection and the reasons for using a particular material for each application is explained.

DESIGN AND FABRICATION OF FLAT CONDUCTOR CABLE

Flat conductor cable has finally achieved a status of a good design technique for applications in avionics equipment, missiles, computers, and space systems; and no longer is considered an infant about which very little is known. Many articles have been written over the past several years on the subject of flat conductor cable, and several excellent technical works have been published. Technical memoranda issued by NASA on design, manufacture and application, the IPC Application Handbook and the more recent Cable and Interconnections Handbook to be published by McGraw Hill under the direction of Charles Harper provide excellent information for the use of flexible etched circuitry and flat conductor cable.

To keep terminologies straight, flat conductor cable refers to continuous cable with long parallel ribbons of copper that are made on a colating machine. The flexible etch circuit or flexible printed wiring is made by a process similar to that used for hard circuit boards. It would be convenient if we could completely separate the two types. However, in most applications today, they compliment each other. Whether we like it or not, the average design engineer encouraged by the services such as the Army, Navy, and Air Force still think primarily in terms of round connectors. It is unfortunate that this is true. However, it will be true for sometime to come and one of the ways of adapting F.C.C. to a round connector is through the use of the flexible etched circuit transition piece. In most space applications considerable weight can be saved by designing cable with very specific configuration and conductor routing joined to a long run of flat conductor cable. Both flexible printed wiring and flat conductor cable should be considered when approaching a new design.

I would like to discuss the design of flat conductor cable primarily from a materials standpoint. We are all going to see how cable is made, and we are going to be given charts and data on current ratings of conductors, minimum conductor widths and spacings. A good deal of practical design data is available from the suppliers' literature and it doesn't take much imagination to arrive at a design which is compatible from an electrical and configuration standpoint.

One of the areas that needs particular attention for cable design is the selection of the materials. Table I provides characteristics of a variety of materials available from which flexible etch circuitry or flat conductor cable can be made. Variations of this table are available in handbooks and other literature. There are other materials not included in this table such as irradiated polyolifin nomex, polycarbonate and new Du Pont adhesive Kapton material. Basically, it indicates that a wide variety of materials are available for cable fabrication. The characteristics listed are strictly material characteristics, not finished cable characteristics. The finished cable characteristics cannot be determined until all of the materials and processes are considered.

Table II shows a listing of the temperature capabilities of the various materials from which cables can be made. From the standpoint of aerospace systems Groups II, III & IV are usually considered. The materials in Group I are not generally used because processing the materials requires extremely high temperatures which are not always practical. On the lower end of the scale materials are thermo plastic, which may be good for commercial types of cable but in aerospace applications they are not usable because of outgassing, low temperature characteristics, moisture absorption, and poor dimensional stability. The first thing in considering materials selection should be the temperature and environment the cable will see. Cable temperature is the sum of the I^2 R loss heat rise in the conductor plus the maximum ambient temperature and must match the capability of the combination of the adhesive and the laminate material or film you intend to use. These materials can be further subdivided by their ability to be used in flexible etched circuitry manufacture and/or flat conductor cable manufacture. Table III is a breakdown of the material usable in these categories. Some are usable in both. It provides a third consideration as to which material may be most suitable for your application.

Table IV details many of the other factors which should be considered for material selection. The numbers which are assigned each attribute are arbitrary numbers based on experience and evaluation. It considers fabrication cost and other factors not shown in the previous tables.

Cables used in the aerospace industry are classified in several categories. Those used in ground test equipment and computer environment, those adaptable to missiles, those that would be considered for AMCS radar and avionics equipment; and finally those which would be used for space. Let us consider several applications in these categories and explore the cable characteristics required in these applications and relate those to the final cable design and material selected. The first example is a computer cable which is used to transmit megacycle pulses over lengths of 10 or 12 feet, with specific characteristic impedance and a minimum pulse shape distortion and low cross talk.

TABLE I. DETAILED CHARACTERISTICS OF VARIOUS INSULATIONS

Characteristic	TFE Teflon[a]	TFE-Teflon Glass Cloth	FEP Teflon[a]	FEP-Teflon Glass Cloth	Kapton Polyimide[a]	KEL-F[b]	PVF Tedlar[a]	Polypropylene	Mylar[a] Polyster	Polyvinyl-Chloride	Polyethylene
Specific Gravity	2.15	2.2	2.15	2.2	1.42	2.10	1.38	0.905	1.395	1.25	0.93
Flammable	No	No	No	No	Self-Ext	No	Yes	Slow Burning	Yes	Self-Ext	Yes
Appearance	Translucent	Tan	Clear Bluish	Tan	Amber	White & Opaque	Clear	Clear	Clear	Translucent	Clear
Bondability with Adhesives	Good[c]	Good[c]	Good[c]	Good[c]	Good	Good[c]	Good[c]	Poor	Good	Good	Poor
Bondability to Itself	Good	Poor	Good	Good	N.B.	Good	Good	Good	Poor	Good	Good
Chemical Resistance	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Good	Good	Excellent	Good	Good
Sunlight Resistance	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Low	Fair	Fair	Low
Water Absorbtion (%)	<0.01/24 hr	0.10/0.68[d]	<0.01/24 hr	0.18/0.30[d]	3/24 hr	0	0.5/2 hr	0.01	0.8/24 hr	0.10	0.01/24 hrs
Volume Resistivity ohm - cm	$>10^{18}$	10^{16}	$>2 \times 10^{18}$	10^{16}	10^{16}	3.1×10^{16}	3×10^{13}	10^{16}	10^{18}	10^{10}	10^{16}
Dielectric Constant $10^2 - 10^8$ Hz	2.2	2.5/5[d]	2.1	2.5/5[d]	3.5	2.5	7.0	2.0	2.8 - 3.7	3.6 - 4.0	2.2
Dissipation factor $10^2 - 10^8$ Hz	2×10^{-4}	7×10^{-4} / 10^{-3} [d]	2×10^{-4}	10^{-4} / 10^{-3} [d]	3×10^{-3} / 14×10^{-3}	15×10^{-3}	9×10^{-3} / 41×10^{-3}	2×10^{-4} / 3×10^{-4}	2×10^{-3} / 16×10^{-4}	14×10^{-2}	6×10^{-3}
Service Temperature Minimum (°C)	-200	-70	-200	-70	-200	-70	-70	-55	-60	-30	-20
Maximum (°C)	250	250	200	200	300	+125	105	100	105	85	60
Tensile Strength psi @ 25°C	3000	20 000[d]	3000	20 000[d]	25 000	4500	13 000	5700	20 000	3000	2000
$N/m^2 \times 10^8$ @ 25°C	0.2067	1.378	0.2067	1.378	1.097	0.31	0.8825	0.3927	1.378	0.2067	0.1378
Modulus of Elasticity psi	58 000	4.0[d]	50 000	4.0[d]	510 000	190 000	280 000	170 000	550 000		50 000
$N/m^2 \times 10^8$	3.930	0.0003	3.394	0.0003	34.623	12.90	19.29	11.713	37.895		3.445
Thermal Expansion in/in/°F × 10^{-6}	(-30°C to 30°C) 55	Low[d]	(-30°C to 30°C) 50	Low[d]	(-14 C to 38°C) 11	(-196°C to 90°C) 48	(-30°C to 30°C) 28	(-30°C to 30°C) 61	(21°C to 50°C) 45	e	(-30°C to 30°C) 100
cm/cm/°C × 10^{-6}	100		90		20	82	50	110	27		180
Dielectric Strength Volts/mil	600	650 1600[d]	2800	650 1600	7000	1100	4000	600	7600	800[e]	585
Sample Size (mils)	15	3	5	3	2	19.2	1	125	1		125

Notes: a. Trademark, E. I. Dupont de Nemours & Co., Inc.
b. Trademark, Minnesota Mining and Manufacturing Co., Inc.
c. Must be treated
d. Depends on % glass cloth
e. Depends on formulation (plasticizer)

Table II.- Recommended Insulation Service Temperature

Material	High Temperature ***	Low Temperature
I. Above 200° C		
Polyimide Film* - Polyimide Adhesive	300° C	-200° C
TFE Teflon, Heat Fused	250° C	-200° C
II. 150° C to 200° C		
Polyimide Film-FEP, Heat Fused	200° C	-200° C
FEP-Teflon, Heat Fused	200° C	-200° C
TFE-Glass-FEP-Bonded Teflon, Heat Fused	200° C	-70° C
II. 125° C to 150° C		
FEP-C Teflon, Heat Fused	150° C	-55° C
Polyimide Film-Phenolic Butyral Adhesive Bonded	150° C	-100° C
FEP-C-Epoxy Adhesive Bonded	135° C	-55° C
Polyimide Film-Epoxy Adhesive Bonded	135° C	-55° C
Polycarbonate, Heat Fused	125° C	-55° C
Monochloro-tri-fluoro Ethylene, heat fused	125° C	-70° C
IV. 100° C		
Polyester Film-Polyester Adhesive Bonded	100° C	-100° C
Polyimide Film-Polyester Adhesive Bonded	100° C	-100° C
V. Below 100° **		
Polyvinyl Chloride, Heat Fused	85° C	-30° C
Polyvinyl Chloride, Adhesive Bonded	85° C	-30° C
Polyester-Polyethylene, Heat Fused	60° C	-20° C
Polyethylene, Heat Fused	60° C	-20° C

* This material is difficult to process and should only be considered for its high temperature capabilities.

** Group V is not generally recommended for space or military spplications, but should be considered for applications where cost is of greatest importance.

*** Temperature rise in the conductor due to I^2R losses must be added to ambient temperature of cable to determine total insulation temperature.

Table III. Fabrication Method

Materials for Fabricating Continuous Flat Conductor Cable	Materials for Fabricating Flexible Etched Circuitry
1. TFE Teflon, Heat Fused	1. Polyimide Film-Polyimide, Adhesive Bonded
2. Polyimide Film FEP, Heat Fused	2. Polyimide Film-FEP, Heat Fused
3. FEP Teflon, Heat Fused	3. TFE Glass-FEP Bonded Teflon, Heat Fused
4. FEP-C Teflon, Heat Fused	4. FEP Teflon, Heat Fused
5. Polyimide Film-Epoxy Adhesive Bonded	5. FEP-C Teflon-Epoxy, Adhesive Bonded
6. Polycarbonate, Heat Fused	6. Polyimide Film-Epoxy, Adhesive Bonded
7. Monochloro-tri-fluoro ethylene, Heat Fused	7. Polyimide Film-Phenolic Butyral Adhesive Bonded
8. Polyester Film-Polyester, Adhesive Bonded	8. Polyester Film- Polyester, Adhesive Bonded
9. Polyvinyl Chloride, Heat Fused	9. Polyimide Film-Polyester, Adhesive Bonded
10. Polyester Film-Polyethylene, Heat Fused	10. Polyvinyl Chloride, Adhesive Bonded
11. Polyethylene, Heat Fused	

Table IV - Flexible Cable - Material Selection Guide

Cable Material / Cable Characteristic	1 Polyimide Film	2 Polyimide FEP Teflon	3 FEP Teflon	4 FEP Glass	5 FEP-C Teflon	6 FEP-C Epoxy Adh.	7 Monochloro-tri-fluoro-ethylene	8 Poly-ester	9 PVC (Self-Ext.)	10 Polyimide Epoxy, Phenolic Butyral	11 TFE Teflon
				CONSTRUCTION BOND							
1 Fusion Bond		X	X	X	X		X		X		X
2 Adhesive Bond	X					X		X		X	
				ENVIRONMENT							
3 Service Temperature °C	1	4	5	3	8	7	8	9	10	6	2
4 Radiation Absorption	1	4	10	9	10	10	10	3	6	2	5
				PHYSICAL FACTORS							
5 Dimensional Stability	4	3	8	3	5	6	7	2	10	1	7
6 Flexibility	7	5	1	8	1	3	3	4	2	6	3
7 Circuit Thickness (.005/.025")	4	2	6	7	3	5	5	1	8	2	7
8 Stripping Ease	7	4	1	6	2	4	1	3	2	5	2
9 Pad Baring Ease	5	3	1	4	1	2	1	2	NR	5	NR
10 Solderability	1	3	4	2	4	2	5	6	7	2	1
11 Welding Thru Ease	NR	NR	3	NR	3	3	3	2	1	NR	3
12 Potting Bondability	3	3	6	3	1	1	5	2	4	3	6
				COST FACTORS							
13 Cost - Raw Material	9	10	4	7	5	6	7	3	1	8	2
14 Cost - Continuous Cbl (without Connectors)	NR	6	5	NR	4	NR	7	2	1	NR	3
15 Cost - Etched Cable (Without Connectors)	9	5	7	6	2	3	8	1	NR	4	NR

LEGEND: 1 = Best Factor; NR = Not Recommended

The cable had to be lightweight, extremely flexible and had to serve as a hinge as shown in slide Figure 1.

Figure 2 shows the conductor configuration used to achieve the electrical characteristics desired. The signal conductors on one layer, are always shadowed by ground conductor on the layer immediately above or below to control cross talk and impedance. Spacings between the conductors were accurately controlled to within ± .003 and the material thickness between the conductors and dielectric constant carefully chosen. The 100 ohm impedance required low dielectric constant material and FEP Teflon was chosen. It had to be a relatively inexpensive cable and again teflon served the purpose; for by using C-20, teflon could be bonded at a high rate of speed in the colator, and hold the conductor tolerance required. To maintain flexibility the cable layers were not bonded but simply fastened on the edges as shown in Figure 3. By stripping each layer of cable, in a regular high speed grinder, we were able to reflow solder the conductors to a cricuit board without difficulty as shown in Figure 4. Soldering was done by a semi-automatic machine.

Another category is cable used in check-out equipment, as shown in Figure 5. In this case, the cable was used in ship board equipment which had to withstand salt spray and humidity. It was made with a fairly thick FEP Teflon primary insulation to control shield capacitance. 24 AWG conductors on 1/10 centers were used to match the pins on the connector. The cable was shielded with solid .0012" copper overlaid with mylar, bonded to the cable and sealed at the edges. The cable was corrugated to increase its flexibility. A flat solid copper shield has an I beam effect and without some type of corrugation the cable is extremely stiff to the point of being almost unuseable. Other types of cables are those used inside of a missile. These cables are fairly rugged and withstand a fair amount of abuse, not only in the actual usage but in installation. Unfortunately there is a long learning curve required for installation and it is not unusual to have a long length of cable stepped on and damaged beyond use. You may design a cable for a missile or airborne system which is extremely light and regret your decision. Figures 6 and 7 show two applications with same type of cable using a perforated copper shield instead of the solid copper shield. The advantage in this particular case is that the copper shield is actually embedded in the teflon and the perforations increase flexibility and at the same time enable the teflon to go through the perforations and seal the cable. EMI protection is not as good as solid copper but it takes a fairly short wave length to penetrate the .040" diameter holes. The main advantage here is ruggedness and the ability of the cable to occupy a small peripheral space next to the skin without corregation. Figure 7 shows 10 layers of cable through a 2" diameter hole. Another rod goes into the

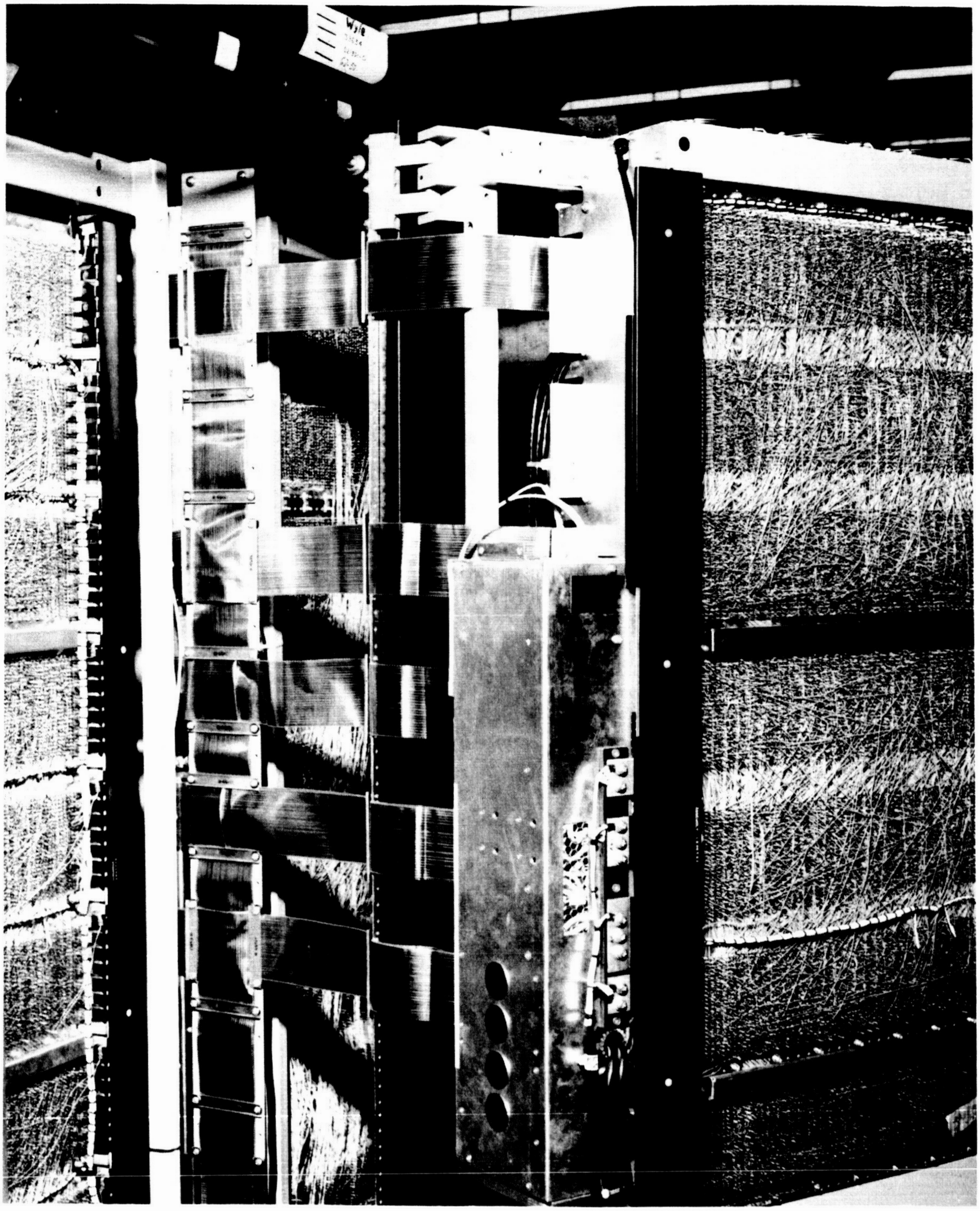
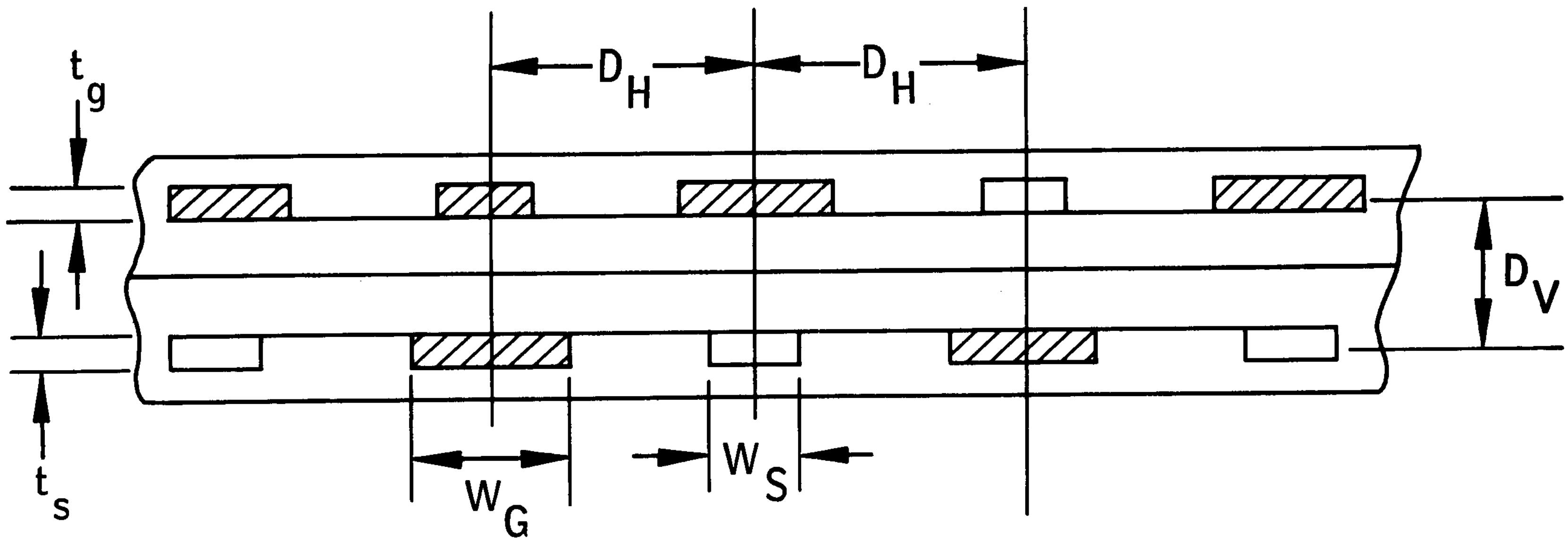


FIGURE I
SHIELD GROUND CONDUCTORS IN COMPUTERS



WHERE

W_S = WIDTH OF SIGNAL CONDUCTOR

W_G = WIDTH OF GROUND CONDUCTOR

t_s = THICKNESS OF SIGNAL CONDUCTOR

t_g = THICKNESS OF GROUND CONDUCTOR

D_H = CONDUCTOR SPACING

D_V = DISTANCE BETWEEN CONDUCTORS

FIGURE 2

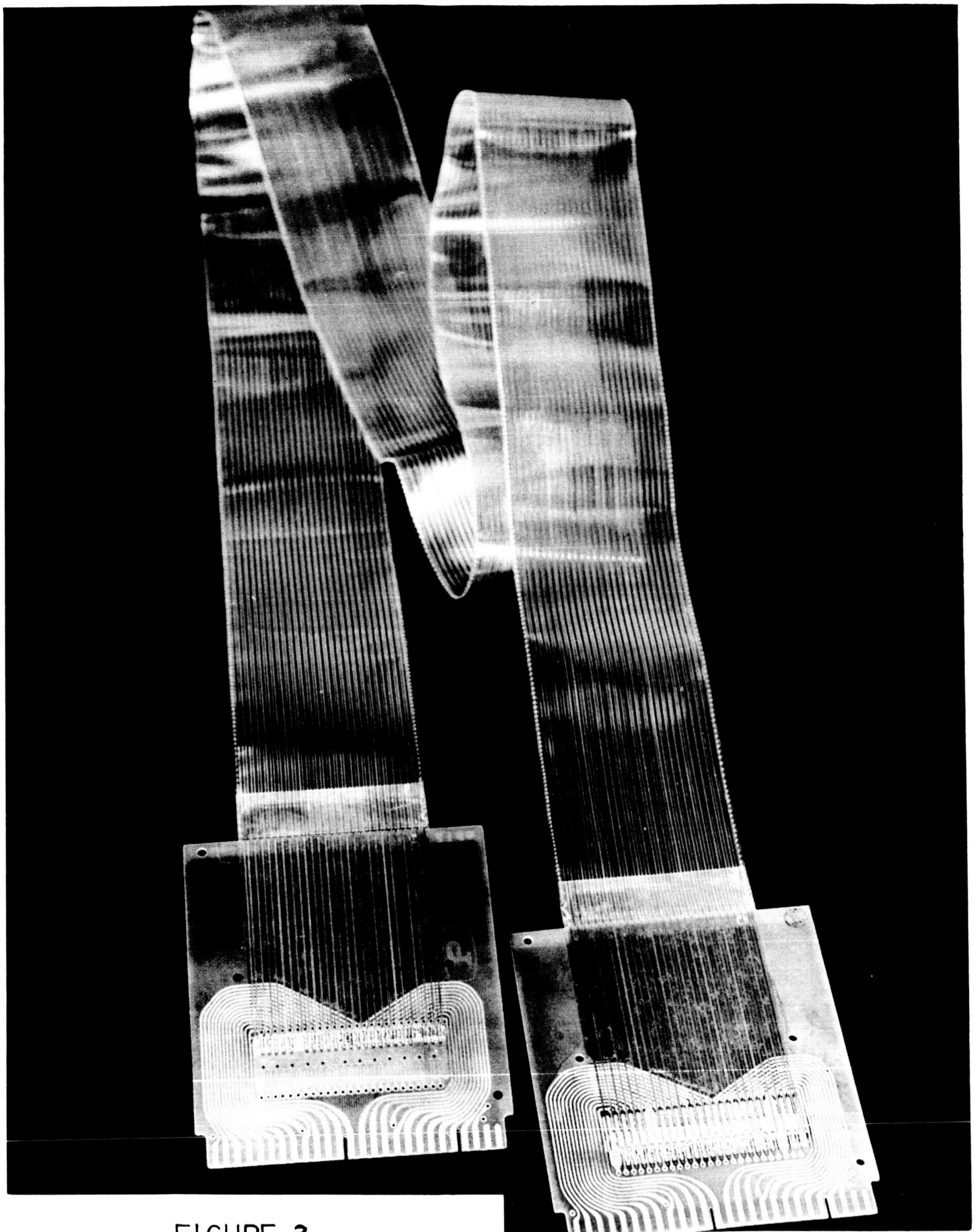


FIGURE 3

GROUND CONDUCTORS AS SHIELDS

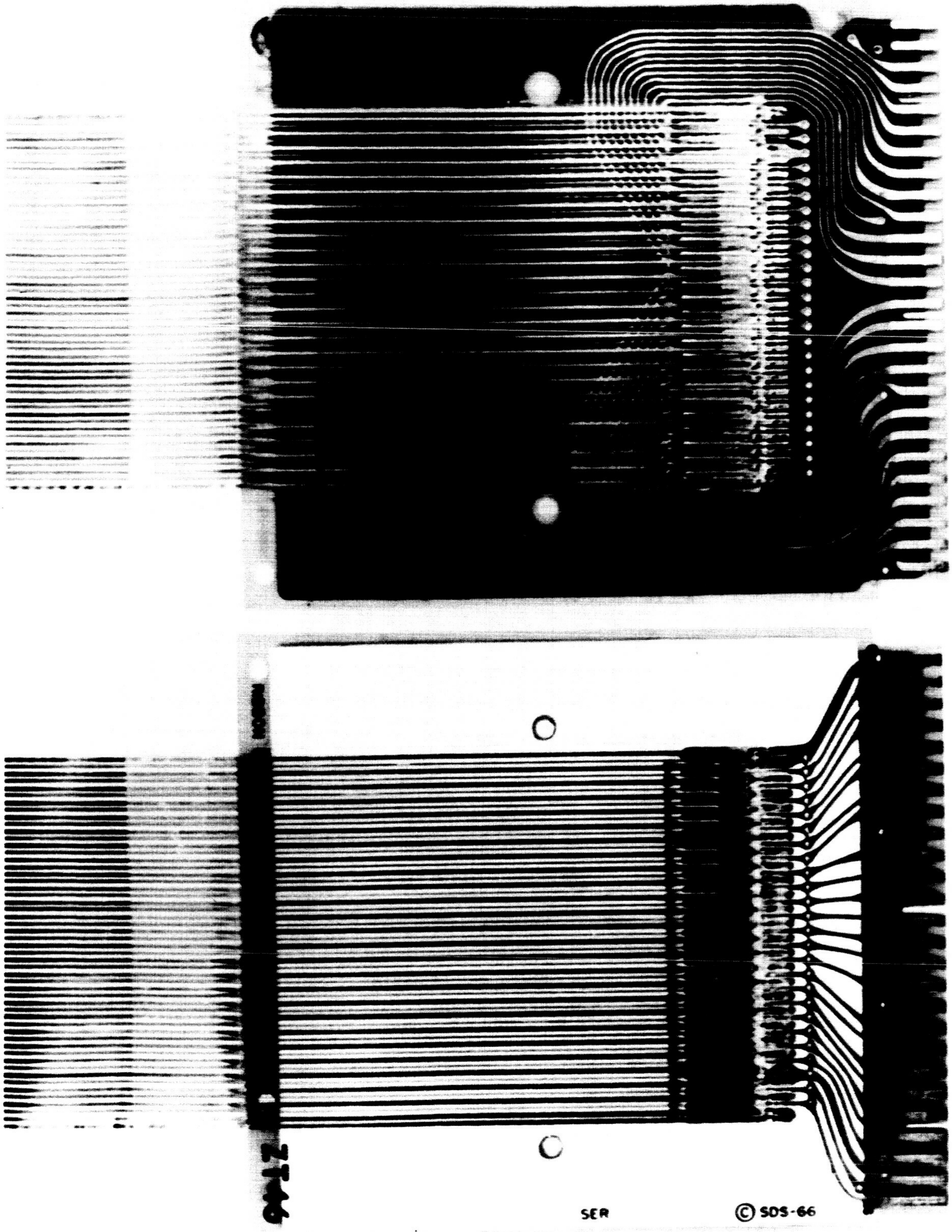


FIGURE 4

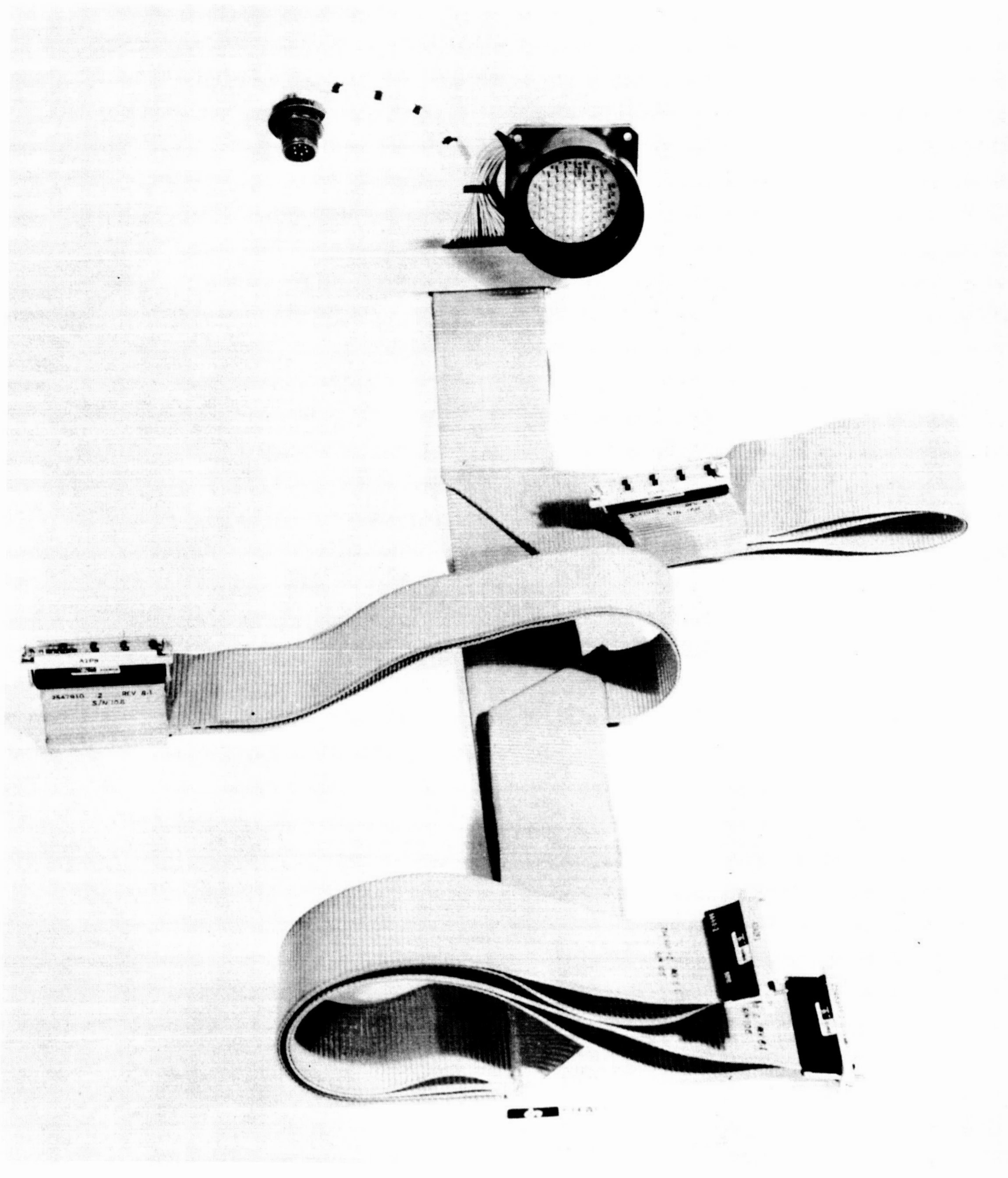


FIGURE 5

SOLID COPPER SHIELD

CORREGATED CABLE

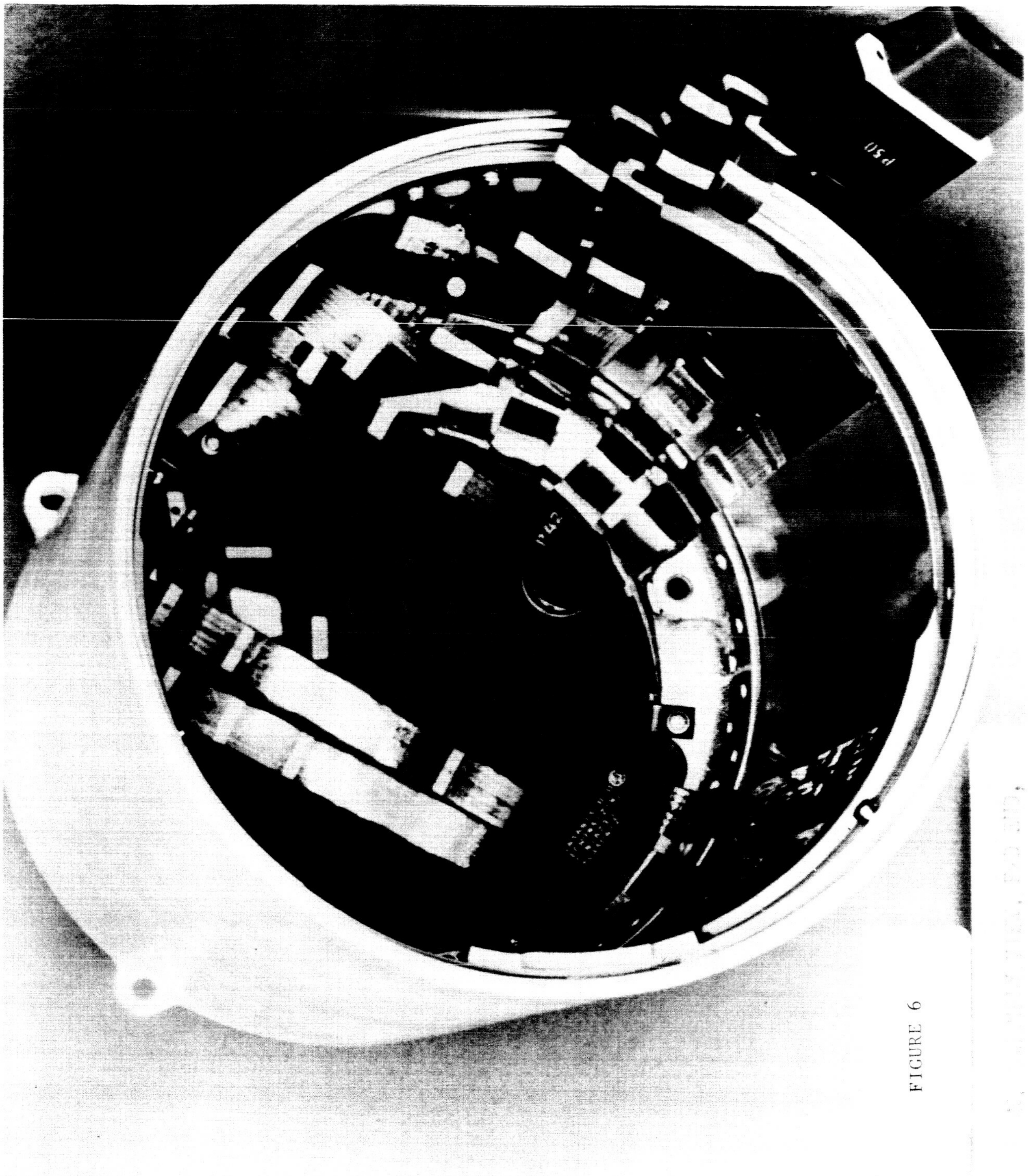


FIGURE 6

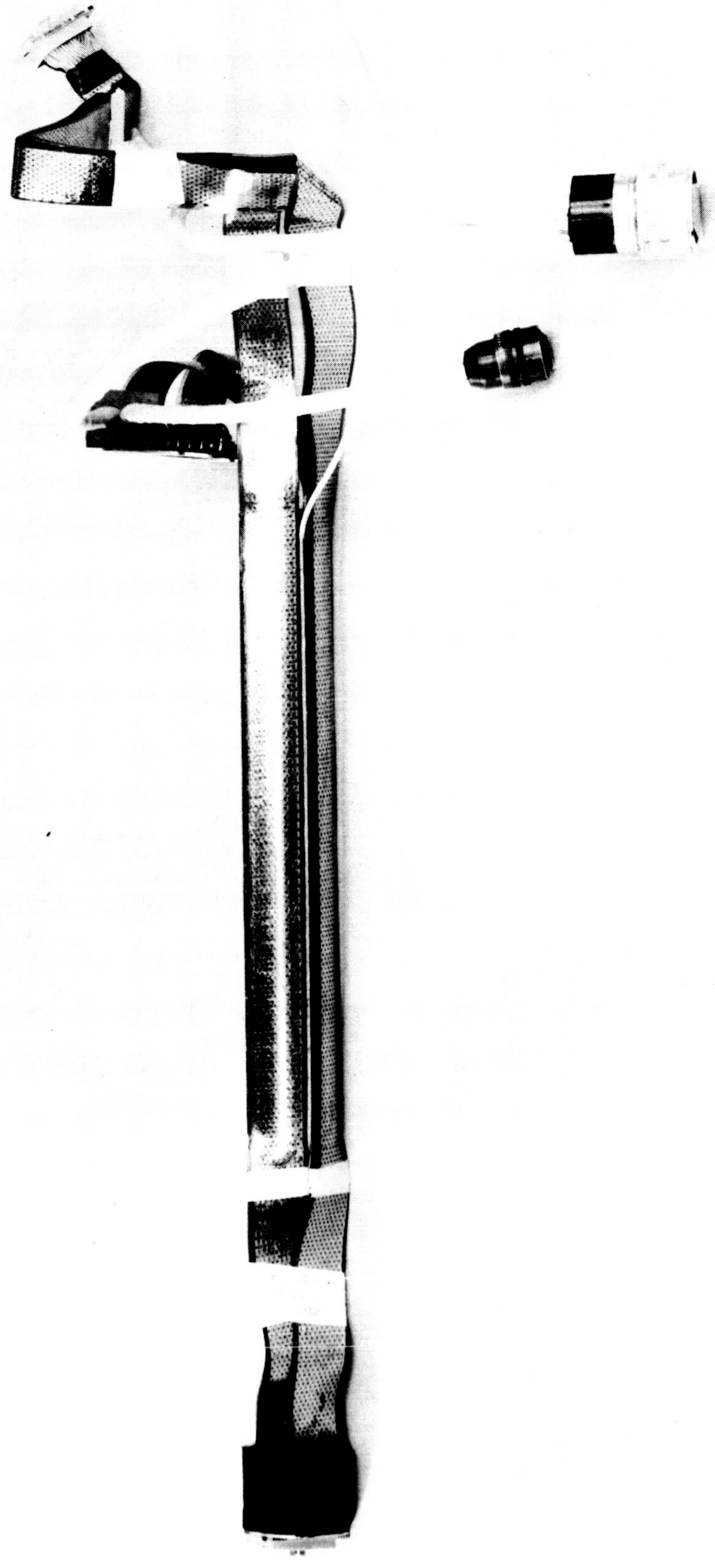


FIGURE 7

same hole. This is a very specific application using 120 shielded conductors in an extremely small space. Figure 8 shows a typical airborne application and illustrates some interesting aspects of design. Here we have a basic Kapton cable consisting of eleven conductors one of which is used as a ground to contact a silver sprayed shield overlayed with a polyurethane coating. It is very thin, very flexible and eleven layers are used. The conductors were 3×25 thousands on 50 thousands centers and it was about as light weight as could reasonably be made. A lazy loop is used to get elevation motion and the cable goes through a rotary joint for azimuth motion. Figure 9 is the unshielded power cable used on the other side of the gimbal system. This is an excellent example of three 22 gauge conductors and one 24 gauge conductor in the same cable thereby reducing copper weight.

Everything in this design worked fine mechanically and electrically until it was given a salt spray test. As you see in figure 10 we had a bad corrosion condition and had to completely redesign the cable as shown in figure 11.

The next category that I would like to talk about is the use of flat conductor cable in space. In space our considerations are environmental, electrical, mechanical, weight and space. Figure 12 which many of you may have seen is the picture of a flat conductor cable taken by a surveyor craft on the surface of the moon. The cable connected the soil sampler to a data processing unit on the surveyor. The conductors were selectively shielded and grounded. The cable was made with Kapton Teflon with a silver shield and an amide-imide conformal coating. Standard connectors were used.

Figure 13 shows an application using 22 layers of cable shielded on both sides through a two axis gimbal system. The 22 layers of cable contained over 700 shielded circuits to interconnect flexible etched circuit cables. The cables were over twelve feet long and were made with only one mil Kapton between shield and conductors. A liquid epoxy adhesive system bonded the cables together in a continuous collated process. The cable was only .008'' thick. This cable when first considered in round wire was estimated to weight approximately 25 lbs. The finished cable with the 22 layers and the connectors on each end weigh 3 lbs.

Figure 14 shows another etched cable being measured for torque. This cable was made with Kapton with a vapor deposit aluminum shield designed in such a way that the shield was continuous all around the cable. The cable has 70 conductors is about 24'' long and weighs only 24 grams. In making the torque measurements the torque of the cables and the bearings could not be resolved but it was estimated the torque required to flex the cable was 3/4 inch ounces.

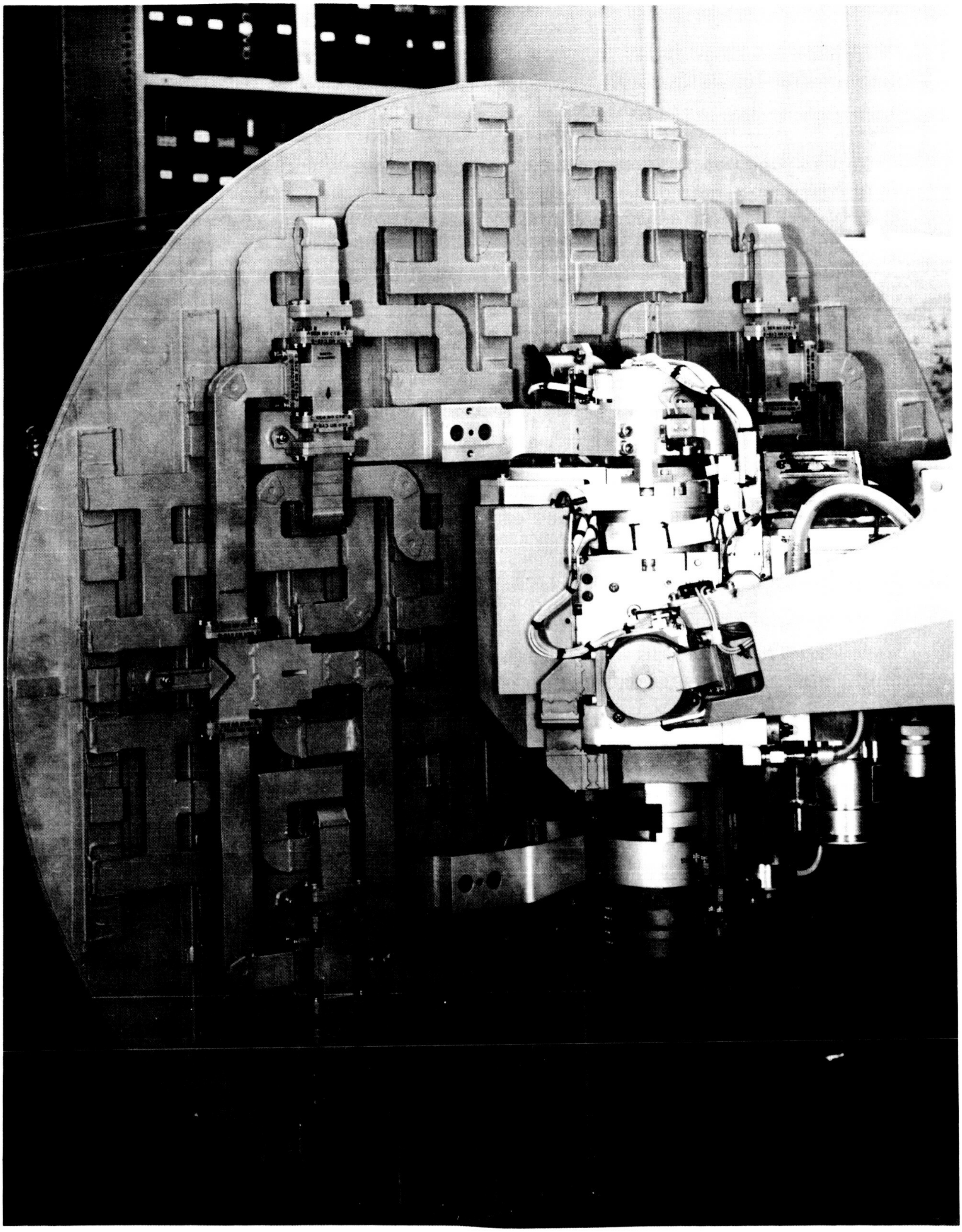


FIGURE 8

FIGURE 9

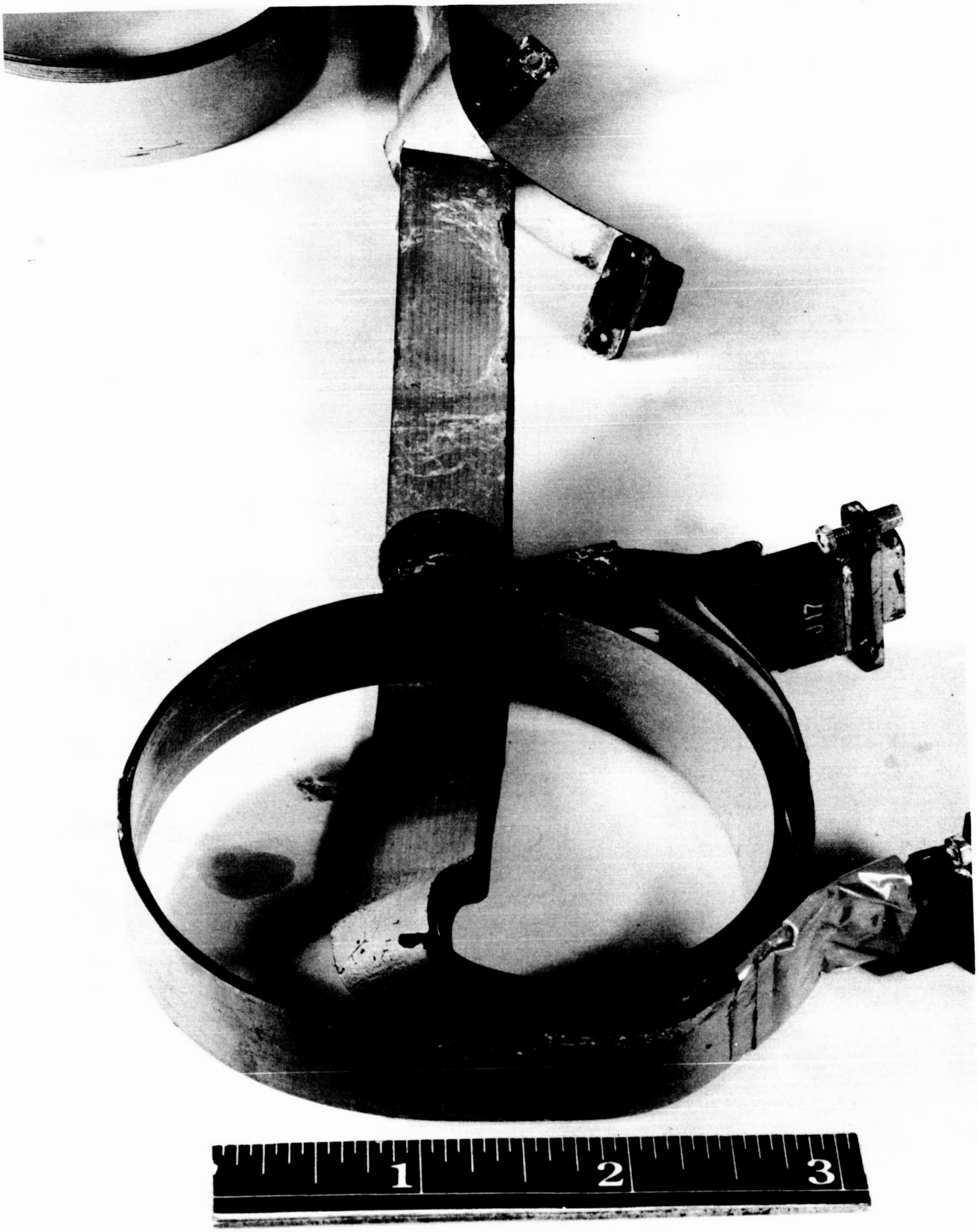


FIGURE 10

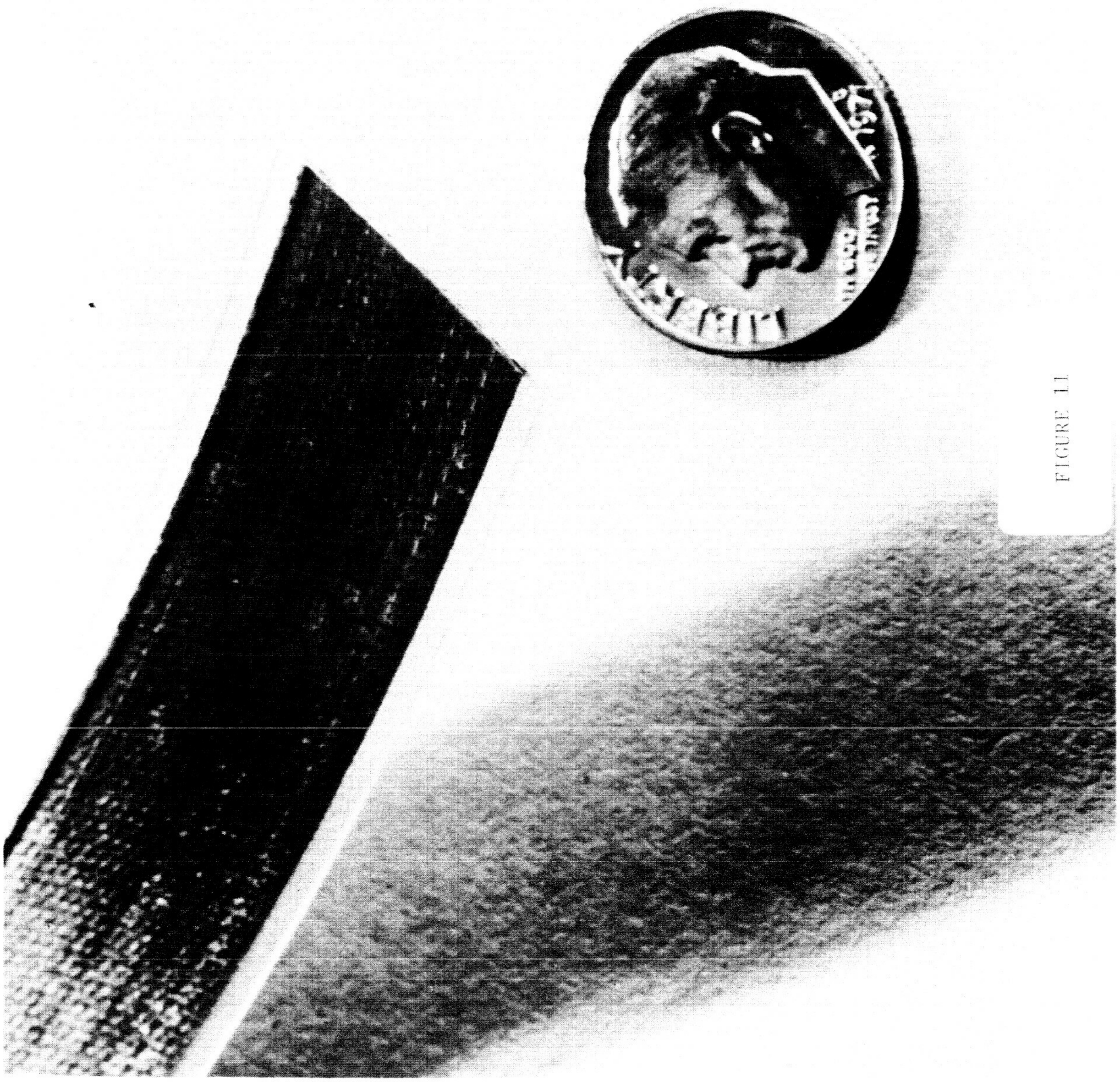


FIGURE 11

FIGURE 12

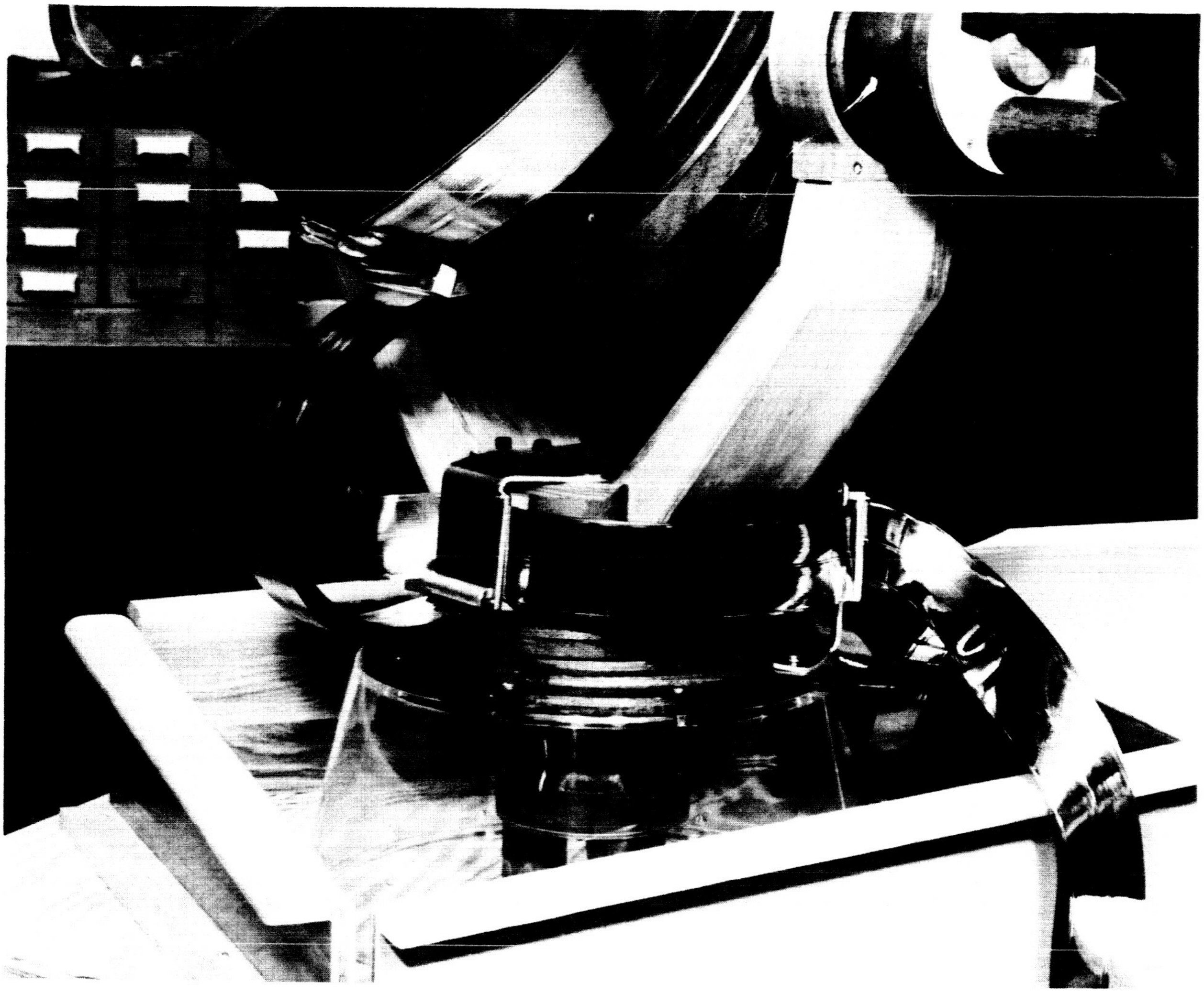


FIGURE 13

VAPOR DEPOSITED SHIELDED CABLE
GIMBAL INSTALLATION

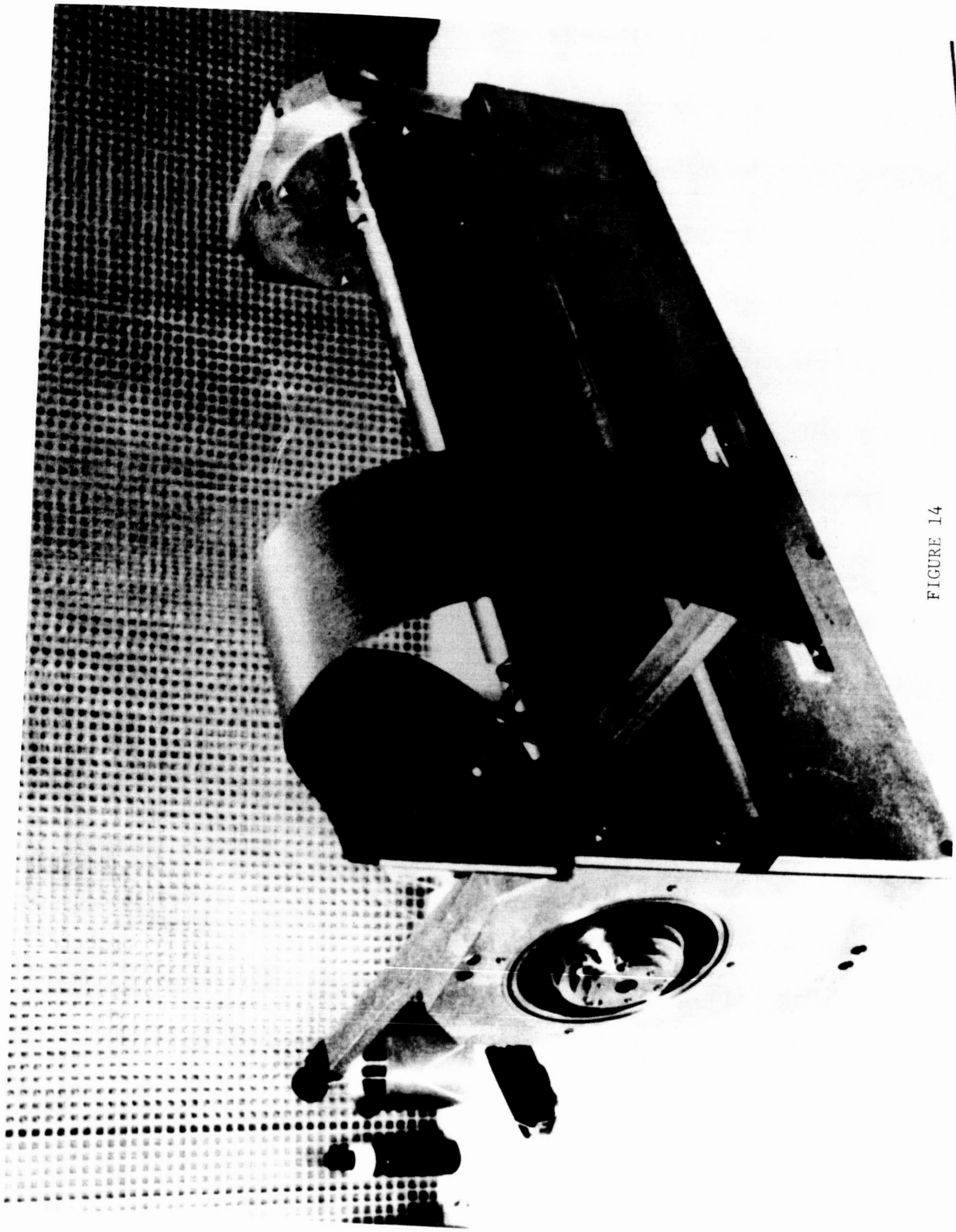


FIGURE 14

The last application shown in Figure 15 is the one that is on the probe that is now on it's way to Jupiter. This cable as you can see is used in a rotary joint and was again made with Kapton with a deposit aluminum shield with an epoxy adhesive system. A most significant feature on this design besides being thin and light in weight is it has an operating voltage in excess of 3,000 volts between shield and the conductor with .002" Kapton. The test voltage used was over 6,000 volts.

This cable is now over 200 million miles in space, has gone through the asteroid belt and is still operating. Adequate spacing between the conductors and laminating processes to eliminate air entrapment were important. The shielding is vapor deposited with an overlay of 1 mil Kapton over the shielding. The most amazing thing about this cable is that were often conventional materials used and they are still functioning at that distance.

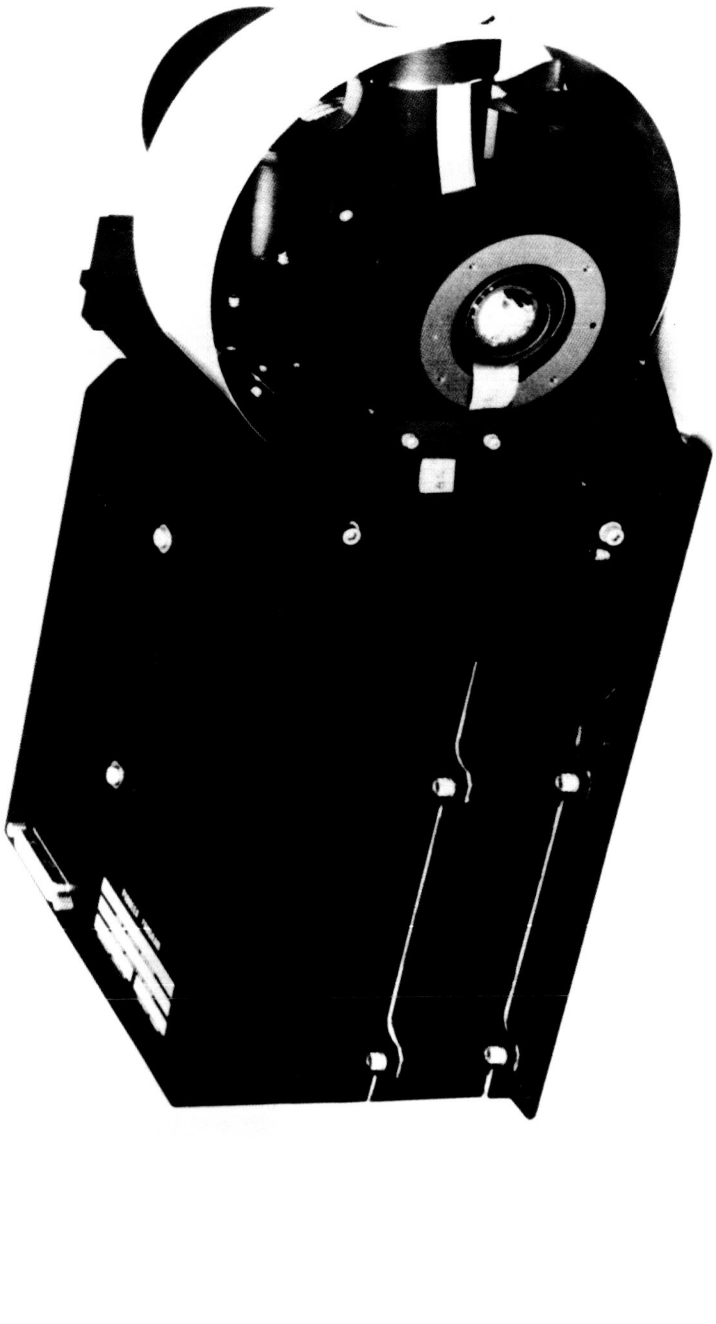


FIGURE 15

HALAR FLUOROPOLYMER — A VERSATILE INSULATION MATERIAL

By A. B. Robertson
Allied Chemical Corp.

INTRODUCTION

The ever-increasing demands of wire and cable users present a difficult problem in materials selection to the wire and cable producer. For instance, the aircraft industry requires wire and cable which is lightweight, nonflammable, inert to hydraulic fluids, and resistant to thermal cycling. The insulation must be rugged in thin wall constructions. The chemical and petroleum industries require wire and cable which will resist corrosive chemicals and organic solvents. Oil-well logging wire, for example, must resist crude petroleum at temperatures as high as 275°F. Some nuclear power applications require insulation which will maintain useful properties on exposure to large dosages of ionizing radiation. These formidable problems point to the need for an insulating material which is rugged, chemically inert, resistant to ionizing radiation, and one which has useful properties over a broad temperature range.

At Allied Chemical, a continuing research program is directed toward developing materials for the wire and cable industry. A new product resulting from this research effort is E-CTFE Copolymer, a fluoropolymer, which has an outstanding combination of electrical, thermal, and mechanical properties. E-CTFE Copolymer was commercialized in 1970 under the Trademark HALAR.

In this paper, the properties of E-CTFE are discussed and compared with those of other commercial fluoropolymers. Particular attention is given to the utility of E-CTFE as a wire and cable insulation.

CHEMICAL STRUCTURE

HALAR resin is made by combining ethylene and monochlorotrifluoroethylene in predominantly 1:1 alternating structure. The repeat unit of the copolymer corresponds to that shown in equation (1).

$$CH_2 = CH_2 + CF_2 = CFCl \rightarrow (CH_2CH_2CF_2CFCl) \tag{1}$$

The material melts at 245°C and has a glass transition temperature at about 93°C.

MECHANICAL PROPERTIES

E-CTFE is a rugged material which is characterized by high tensile and impact strength and excellent creep resistance. Its properties are summarized

in Table 1. The tensile strength of E-CTFE is 2 to 3 times higher than that of fluorinated ethylene-propylene copolymer (FEP) and equal to that of polyvinylidene fluoride (PVF_2). The stiffness of E-CTFE is moderate, greater than that of FEP, but slightly lower than that of PVF_2. The cold-flow resistance of E-CTFE is comparable to that of PVF_2. Both polymers are markedly superior to FEP in this regard. The impact strength of E-CTFE at ambient and subambient temperatures equals that of FEP and is much superior to that of PVF_2. E-CTFE also exhibits excellent cut-through and abrasion resistance.

This combination of properties makes E-CTFE particularly suited for wire and cable insulation. It is a rugged insulation which will withstand considerable mechanical abuse.

ELECTRICAL PROPERTIES

In addition to being rugged, E-CTFE also exhibits the excellent electrical properties listed in Table 2 and shown graphically in Figures 1 and 2. Like FEP and PTFE, E-CTFE has exceptionally low ac loss properties. All of these materials are superior to PVF_2 in this regard. The dielectric constant of E-CTFE measures 2.5 to 2.6 over the frequency range of 10^2 to 10^6 Hz. Its dielectric constant is independent of temperature up to at least 300° F (Fig. 1). The dissipation factor of E-CTFE is low, ranging from 0.0008 to 0.015 depending on frequency and temperature (Fig. 2). Additional electrical properties of interest include a dielectric strength of 2000 volts per mil for a 10-mil wall and a volume resistivity of 10^{15} ohm-cm. From an electrical standpoint, the performance of E-CTFE compares favorably with that of FEP and is much superior to that of PVF_2.

The typical wire properties shown in Tables 3 and 4 confirm that the electrical properties are readily translated into performance as a wire insulation.

THERMAL PROPERTIES

E-CTFE has a broad-use temperature range. It melts at about 245°C and exhibits good stability during processing at temperatures in the range of 260° to 280°C. The continuous-service temperature for uncrosslinked E-CTFE is 150°C. The useful life of E-CTFE insulation at this temperature is rated as greater than 10 000 hours. Short-term exposures to temperatures above 150°C are tolerable.

E-CTFE also exhibits remarkable toughness at subambient temperatures. It has good impact strength at temperatures as low as -80°C. Its behavior in impact tests compares favorably with that of FEP and is much superior to that of PVF_2.

THERMAL STRESS CRACKING

E-CTFE, like E-TFE and some other polymers, will crack at sufficiently high temperatures. This phenomenon shows a well-defined molecular weight dependence, with resistance to stress cracking increasing with increasing molecular weight. A mandrel wrap test (Mil-L-P-390-C, Part H) at 10 to 15 percent strain indicates that uncrosslinked E-CTFE may stress crack at temperatures above 170°C. Crosslinked E-CTFE is resistant to stress cracking at temperatures up to at least 200°C.

CHEMICAL RESISTANCE

The chemical resistance of E-CTFE is excellent. It is inert to acids, bases, and strong oxidizing agents at ambient and elevated temperatures. No known solvent dissolves or stress cracks E-CTFE at temperatures at least as high as 125°C. Less than 1 percent weight change and no effect on physical properties occur when E-CTFE is exposed at 55°C for 1 week to the chemicals listed in Table 6.

Wire constructions insulated with E-CTFE are compatible with lube oil, jet fuel, and aircraft fluids such as SKYDROL[1] and AEROSAFE.[2] Wire insulated with E-CTFE exceeds military performance requirements for cracking resistance on immersion in this substances.

PERMEABILITY CHARACTERISTICS

E-CTFE also exhibits very low permeability characteristics. Its water vapor permeability of 0.6 gm-mil/100 in.^{2}/24 hours at 100°F is six times lower than that of PVF_2. Its permeability to common gases, i.e., oxygen, nitrogen, and carbon dioxide, is 10 to 30 times lower than that of FEP. The oxygen permeability of E-CTFE measures 25 cc-mil/100 in.^{2}/24 hours/atm at 23°F.

1. Registered Trademark of Stauffer Chemical
2. Registered Trademark of Monsanto Co.

The low permeability characteristics of E-CTFE account for its excellent performance as an insulation for use in aqueous environments. In a simulated brackish water environment, a 30-gauge conductor insulated with 4 mils of E-CTFE has performed at 40 volts dc for 2500 hours. A similar conductor insulated with PVF_2 was severely corroded after 700 hours. Throughout the test, the wall resistance of the E-CTFE insulation remained above 10^{11} ohms. The wall resistance of PVF_2 decreased to 10^4 ohms after 1000 hours. The better insulating characteristics of E-CTFE in this test are believed to be related to its lower absorption of ionic substances.

FLAMMABILITY

Flammability resistance is one of E-CTFE's outstanding properties. E-CTFE does not melt or drop when exposed to direct flame. When placed in a flame, it chars. On removal of flame, it immediately extinguishes. E-CTFE will not support combustion in atmospheres which contain up to 64-percent oxygen. Table 7 compares the flammability characteristics of E-CTFE to those of other fluoropolymers.

The flammability resistance of E-CTFE Copolymer is superior to that of E-TFE Copolymer. The oxygen index of E-CTFE is 64; that of E-TFE is 30. In vertical burn tests, E-CTFE insulated wire extinguishes immediately on removal of the ignition source. E-TFE insulation exhibits significant after burn in verticle tests (Table 7).

PROCESSING

E-CTFE Copolymer is melt processable at stock temps of 500° to 550°F. Its rheological characteristics at 520°F compare with those of extrusion grade high density polyethylene at its nominal processing temperature, 375°F (Fig. 3). E-CTFE insulation has been extruded by tube-on and pressure techniques in wall thicknesses ranging from 2 to 80 mils. Extrusion rates up to 400 ft/min have been obtained. It has been extruded over a variety of conductors including bare copper, tin-plated copper, silver-plated copper, and copper ply steel.

Three grades of HALAR E-CTFE resin are available for wire and cable insulation. HALAR 301 resin is a general purpose grade which is designed for applications requiring continuous service upto 150°C. Its nominal melt processing temperature is 520°F. HALAR 500 resin is a high flow grade designed for high extrusion rates and/or thin wall constructions. Its nominal melt

processing temperature is 500°F. HALAR 500 resin is recommended for continuous service up to 135°F. HALAR 502 resin is a radiation sensitized grade. Its processing characteristics are identical to HALAR 500 resin.

RADIATION CROSSLINKING

E-CTFE crosslinks when exposed to ionizing radiation, Cobalt 60, or electron beam dosages as low as 5 megarads are sufficient to render sensitized E-CTFE nonflowing above its normal melting temperature of 464°F. Radiation crosslinking makes E-CTFE resistant to thermal stress cracking at temperatures at least as high as 200°C. In addition, crosslinking improves the cut-through and abrasion properties of E-CTFE at temperatures above 150°C.

E-CTFE also has remarkable resistance to radiation. It maintains useful properties on exposure to dosages as high as 500 megarads (Table 8). The high tolerance to radiation exhibited by E-CTFE makes it particularly suited as an insulation for use in nuclear power applications.

CONCLUSION

In summary, it may be stated that E-CTFE offers a unique combination of properties heretofore unobtainable in a single material. Its chemical resistance, flammability characteristics, and electrical properties compare favorably with those of perfluorinated polymers. Its mechanical properties, especially its toughness, are superior to those of other fluoropolymers. E-CTFE can be melt processed with reasonable ease.

This combination of properties makes E-CTFE particularly suited for demanding wire and cable applications. A single layer of E-CTFE insulation offers many properties which previously were obtainable only in jacketed constructions. Some applications for which E-CTFE is suited include computer wire, locomotive wire, logging cable, aircraft hook-up wire, and nuclear power cable.

TABLE 1. COMPARATIVE PROPERTIES OF VARIOUS FLUOROPOLYMERS

Physical-Mechanical Property	E-CTFE (Halar™ 300)	FEP (Teflon 110)[a]	PVF_2 (Kynar 300)[b]
Specific gravity	1.68	2.15	1.78
Tensile at 73°F			
Stress at yield, psi	4000 to 5000	2000 to 2500	5000 to 7000
Stress at break, psi	5000 to 7000	2000 to 3000	5000 to 7000
Elongation at break, %	220	250	200
Flex at 73°F			
Modulus, psi	240 000	90 000	250 000
Stress at yield, psi	7 000	3 000	7 000
Creep modulus			
at 1500 psi, 250 hr, 73°F	90 000	7 000	90 000
Hardness, Rockwell R.	93	45	109
Drop weight impact, ft-lb/in.			
at 73°F	>140	>140	35
at -85°F	35 to 95	40	<5
Armstrong abrasion, volume loss cc	0.3	0.6	0.3

a. Registered Trademark of E.I. DuPont de Nemours and Company.
b. Registered Trademark of Pennwalt Corporation.

TABLE 2. ELECTRICAL PROPERTIES OF VARIOUS FLUOROPOLYMERS

	E-CTFE (Halar™ 300)	FEP (Teflon 110)	PVF_2 (Kynar 300)
Dielectric Strength			
Volts/Mil			
125 mils	480	500	250
40 mils	1000	900	650
10 mils	2000	2000	1280
Dielectric Constant at			
10^2 Hz	2.6	2.1	8.4
10^3 Hz	2.5	2.1	7.7
10^6 Hz	2.5	2.1	6.4
Dissipation Factor at			
10^2 Hz	0.0008	<0.0002	0.049
10^3 Hz	0.003	<0.0002	0.019
10^6 Hz	0.013	0.0007	0.170
ARC Resistance, sec.	135	>360	60
Volume Resistivity, ohm-cm	10^{15}	10^{18}	2×10^{14}

TABLE 3. TYPICAL PROPERTIES OF HALAR AIRCRAFT HOOK-UP WIRE

Property	Value
Insulation Thickness	10 mils
Conductor	19 × 32 stranded tinned copper
Insulation Elongation, %	205
Insulation Tensile Strength, psi	6300
Insulation Resistance, ohms/ft	2×10^{13}
Low Temperature (-65°C) Cold Bend	Passes[a]
Life Cycle at 180°C	Passes[a]
Smoke Generation	Passes[a]
Verticle Flammability	Passes[a]
Dielectric Strength	
As received, kV	18.7
After 4 days at 200°C, kV	13.5
Dissipation Factor at 10^3 Hz	0.009
Dielectric Constant at 10^3 Hz	2.5

a. Tests run per proposed Mil Spec. 22759/13.

TABLE 4. TYPICAL PROPERTIES OF HALAR COMPUTER WIRE

Property	Value
Insulation Thickness	0.004 in.
Conductor	30-Gauge, Solid Copper
Insulation Elongation, %	160
Insulation Tensile Strength, psi	7000
Insulation dc Resistance, ohm/ft	2.5×10^{12}
Wet Dielectric Test at 2000 Volts	Passes[a]
Cold Bend at -54°F, 1-in. Mandrel, 1/4 pound load	Passes[a]
Cut Through at 800 Gram Load	Passes[a]
Cold Flow at 550 Gram Load	Passes[a]
Shrinkage at 200°C for 96 hours	0.062 in.
Dielectric Constant at 10^3 Hz	2.5
Dissipation Factor at 10^3 Hz	0.009

a. Tests run per proposed Mil Spec 81822/13.

TABLE 5. THERMAL PROPERTIES OF E-CTFE AND OTHER FLUOROPOLYMERS

Property	E-CTFE (Halar™ 300)	FEP (Teflon 110)	PVF_2 (Kynar 300)
Melting Point, °C	245	275	172
Continuous Service Temperature, °C	150	200	135
Heat Distortion, °C			
at 66 psi	117	70	145
at 264 psi	78	51	90
Low Temperature Embrittlement, °C	<-80	<-80	<-80
Coefficient of Liner Thermal Expansion, in./in.-°F	14×10^{-5}	10×10^{-5}	---

TABLE 6. HALAR CHEMICAL RESISTANCE

-less than 1% weight change and no significant effort on tensile properties after 7 days immersion at 55°C in:

Aniline	Ethylene Glycol	Skydrol 500A
Xylene	Bromobenzene	Toluene
Nitrobenzene	Butyl Alcohol	Heptane
1 to 37% Hydrochloric Acid	1 to 98% Sulfuric Acid	Dimethyl Formamide
		1 to 70% Nitric Acid
1 to 50% Sodium Hydroxide	1 to 25% Ferric Chloride	Mineral Oil
Jet Fuel JP4	Hydraulic Fluid	Aerosafe 2300

TABLE 7. FLAMMABILITY CHARACTERISTICS OF VARIOUS FLUOROPOLYMERS

	E-CTFE (Halar 300)	E-TFE (Tefzel 200)	FEP (Teflon 110)
Oxygen Index, ASTM D2863	60	31	95
ASTM D635	Nonburning	Nonburning	Nonburning
UL Vertical, 1/16 Classification (1) Burning Behavior	SE-O Chars	SE-O/SE-1 Melts & Drips	SE-O Melts & Drips
Mil Spec 22759/13, Flame Out Time, sec			
Single Wire (15' Ignition)	<1	15.2	<1
Single Wire (10' Ignition)	<1	4.5	<1
Bundle (15' Ignition)	<1	5.7	<1

TABLE 8. EFFECT OF COBALT-60 RADIATION ON THE STRESS-STRAIN PROPERTIES OF HALAR RESIN

Cobalt-60 Dosage, Megarads	At 23°C Breaking Strength (psi)/Elongation (%)	At 200°C Breaking Strength (psi)/Elongation (%)
0	7000/210	250/24
5	7000/200	650/488
25	6000/160	700/410
50	4600/100	600/350
100	4200/65	---
500	4000/20	---
1000	2800/10	---

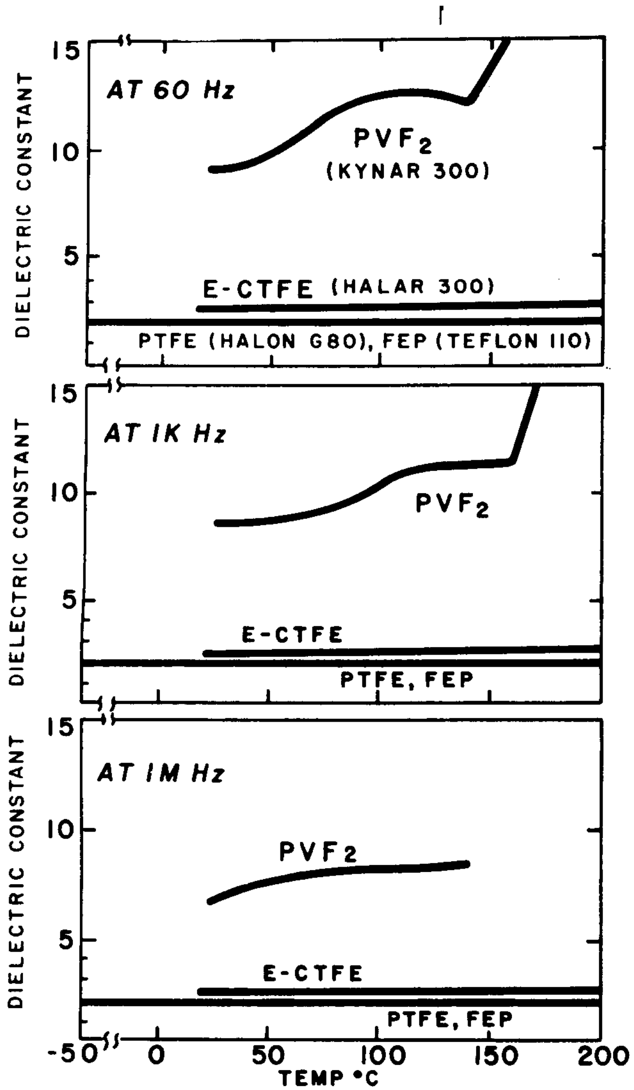


Figure 1. Dielectric constant versus temperature.

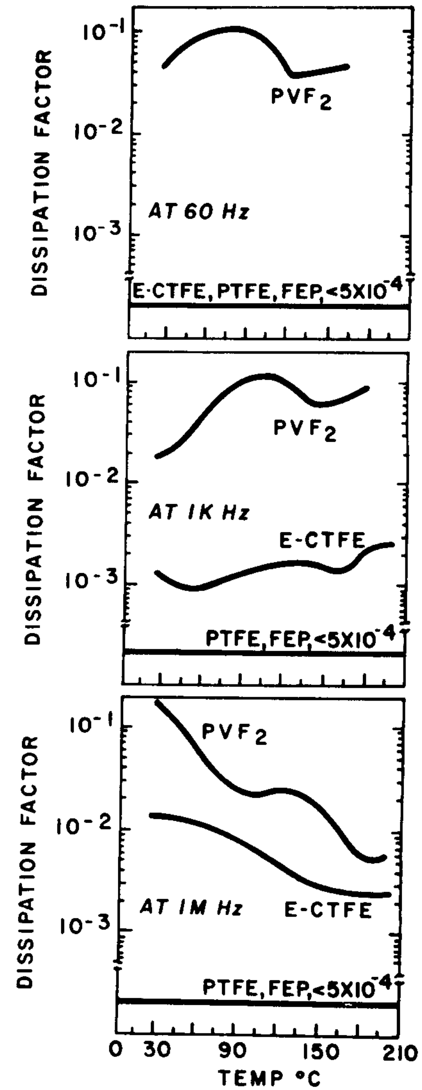


Figure 2. Dissipation factor versus temperature.

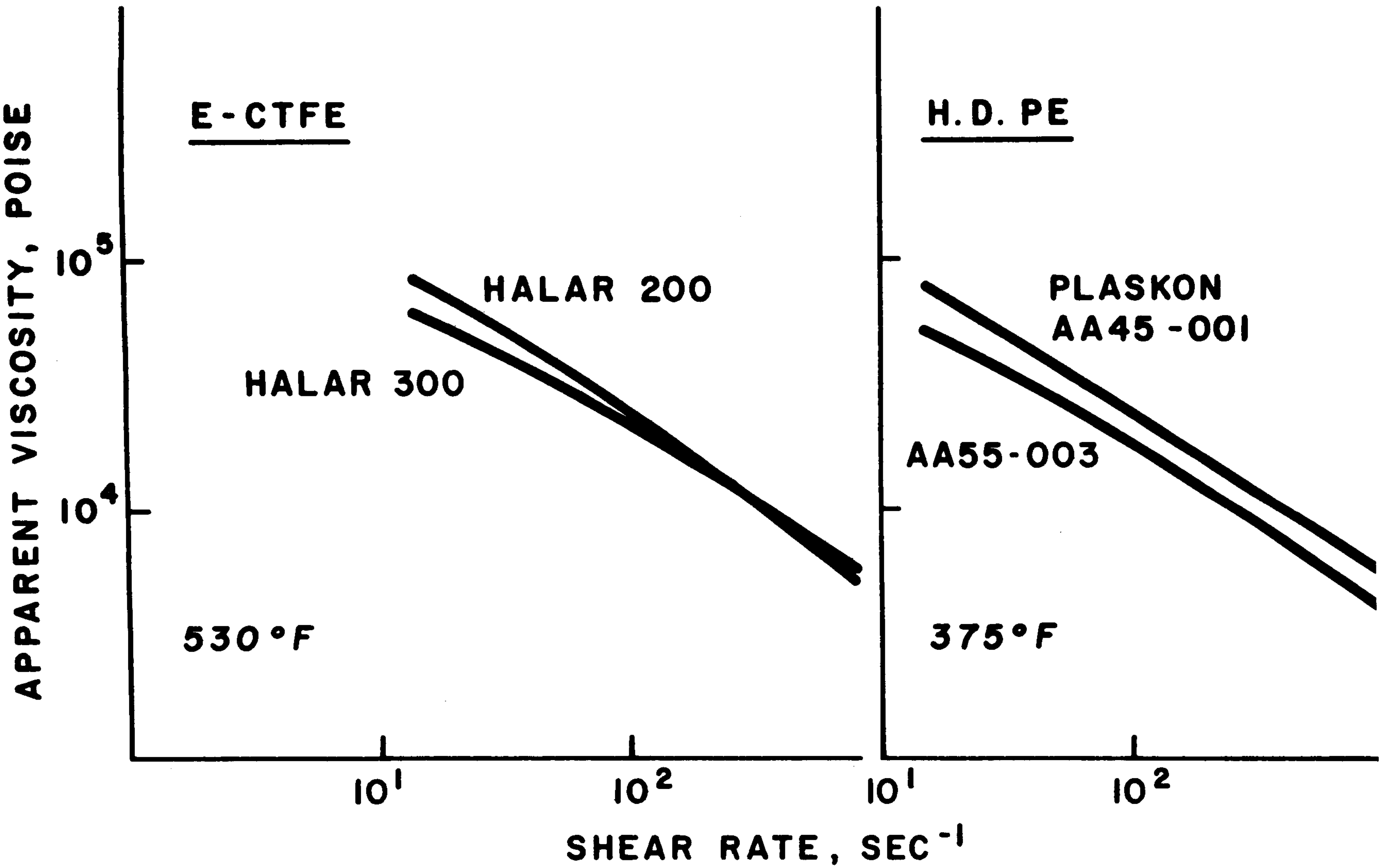


Figure 3. Flow Behavior.

THERMAL CHARACTERISTICS UNDER LOAD

By Dr. Robert F. Carlton
Middle Tennessee State University

A MATHEMATICAL MODEL DESCRIBING THE THERMAL BEHAVIOR OF FLAT CONDUCTOR CABLE UNDER LOAD

ABSTRACT

A theoretical study has been made of the temperature profile in a flat conductor cable. The conductor temperature rise has been determined under full load and partial load conditions in an air environment as a function of the current. Similar results have been obtained for the fully loaded single cable in vacuum and also for the case of one side of the cable in contact with a heat sink. The results are in good agreement with experimental values, where available.

I. INTRODUCTION

The temperature profile inside a medium containing internal heat sources is dependent upon the heat delivered to the surface and the rate at which heat can be dissipated at the boundary. In general the heat dissipation will be via a combination of convection and radiation heat transfer, while the heat delivered to the surface will be dependent upon the nature of the heat source (continuous or discrete) and its magnitude per unit volume, Q (cal/sec), the thermal conductivity, k, of the medium, and the presence or absence of heat sinks.

For cases in which there is symmetry along one direction, the temperature distribution T (x,y) in the steady state will be determined by the two-dimensional Poisson equation

$$\frac{\partial^2 T(x,y)}{\partial x^2} + \frac{\partial^2 T(x,y)}{\partial y^2} = -\frac{Q(x,y)}{k} \qquad [1]$$

subject to the boundary conditions applicable at the surface of the heat conducting medium. In favorable cases an analytical solution will be possible and, in fact, many solutions are available in text and reference works. Even when the boundary and internal conditions for such cases are relatively "mild", the solutions must often be expressed in terms of a complicated series expansion. There are many practical situations for which an analytical solution has not been developed. Indeed such development may not even be practical.

Such is the case with FCC which is complicated by complex boundary conditions, heterogeneous system conditions, and discrete internal heat sources. Hence

the most fruitful approach leading to the prediction of a temperature profile in FCC under ambient and space simulated conditions, load and no load conditions, and in single and stacked-cable configurations lies in the numerical finite-difference approach. In this approach we replace the actual continuous temperature distribution throughout the medium by fictitious heat conducting rods connected between small nodal points as shown below:

$$\begin{array}{ccccc} & & i,j-1 & & \\ & & | & & \\ i-1,j & \bullet - - & i,j & \bullet & i+1,j \\ & & | & & \\ & & i,j+1 & & \end{array}$$

Thus finite differences are used to approximate differential increments in the temperature and the space coordinates. The smaller we choose these finite increments the more closely we approach the true temperature distribution. The temperature gradients involved for the point (i,j) may be written as:

$$\left.\frac{\partial T}{\partial x}\right)_{i+\frac{1}{2},j} = \left(T_{i+1,j} - T_{i,j}\right)/\Delta x$$

$$\left.\frac{\partial T}{\partial x}\right)_{i-\frac{1}{2},j} = \left(T_{i,j} - T_{i-\frac{1}{2},j}\right)/\Delta x$$

$$\left.\frac{\partial^2 T}{\partial x^2}\right)_{i,j} = \left[\left(\frac{\partial T}{\partial x}\right)_{i+\frac{1}{2},j} - \left(\frac{\partial T}{\partial x}\right)_{i-\frac{1}{2},j}\right]/\Delta x = \left(T_{i+1,j} + T_{i-1,j} - 2T_{i,j}\right)/\Delta x^2$$

and similarly for the y direction. In this approximation, the Poisson equation becomes:

$$T_{i-1,j} + T_{i+1,j} + T_{i,j-1} + T_{i,j+1} - 4T_{i,j} = -\frac{Q}{k}$$

and the temperature at a point (i,j) is determined by the temperature of adjacent surrounding nodes. This approach is equivalent to writing an equation to express the net heat flow into each node. For a nodal point on the surface where heat transfer could be by convection and radiation, the equation would be (for a point i):

$$\sum_{j} \frac{kA}{\Delta x}(T_j - T_i) + hA\,(T_o - T_i) + \sigma \varepsilon A\,(T_t^4 - T_i^4) + Q = 0 \qquad [2]$$

where the j index runs over adjacent points within the conducting medium, h is the film coefficient of convection, σ is the Stefan-Boltzman constant, ε is a combination of emissivity and shape factor and A is the area through which the heat flows. This equation can be solved for the temperature T_i for each of the nodes in the network. An iterative technique may then be used to determine the best combination of temperatures for the network. This is accomplished by first assuming a temperature for each node. Then new temperatures are calculated according to equation (2). This process is then repeated until successive values for all T_i differ by an amount δ which is sufficiently small for the accuracy desired.

Calculations have been made for 2" wide FCC containing 4 x 40 mil Ni plated Cu conductors in air and vacuum conditions for a single cable configuration under full load and partial load conditions, using the finite-difference iterative technique.

The difference of the final results from the true temperatures will depend on the fineness of nodal grid used. If an analytical solution were developed, the result would be exact only to the extent that the resulting complex series

expansions could be numerically evaluated. In many cases this may exceed the error from using a finite grid size in order to reduce computer time and memory requirements. For the case at hand, it will be shown that a small grid is not essential, resulting in only a small change in final results.

In what follows, the assumptions made will be presented, the various grids used will be discussed, and the results of the above calculations will be presented and compared to the experimental results.

II. FINITE DIFFERENCE MODELS

The choice of grid network to use is influenced by the geometric configuration of the system under consideration and the desire to minimize the number of nodal points and thus the computing time. However, the reduction in the number of nodal points will result in a poorer approximation to the true values. The interior arrangement of the FCC dictates a grid network composed of rectangular segments the size of the conductors. Hence a rectangular grid network has been chosen which is consonant with the conductor geometry.

For the single cable configuration, two grid networks have been used as shown in Figure 1. For the fine grid, the thermal conductivity of Kapton and FEP have been used, and the second layer of nodal points lie along the Kapton-FEP interface. Since the thermal conductivity of copper is approximately 1000 times that of Kapton or FEP, the conductor has been assumed perfect and thus that all points on the conductor are at the same temperature. Thermal contact resistance at the various interfaces within the cable have been assumed negligible, and the only mechanism used inside the cable for heat transfer is that of conduction. The heat conduction between two nodal points is dependent upon

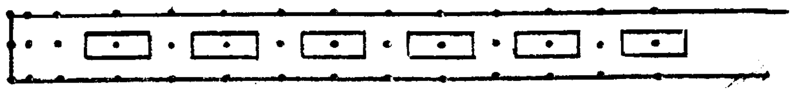


Figure 1a: Coarse Grid

Figure 1b: Fine Grid

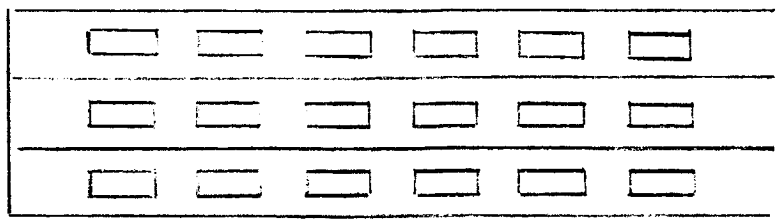
Figure 1: Single Cable Finite-Difference Grid Networks

the thermal conductivity of the intervening medium, the area normal to the direction of heat flow, and the temperature gradient between the two points.

For the coarse grid the nodal points along the Kapton-FEP interface have been omitted and the thermal conductivity of the medium between the conductor and the surface has been taken to be $k = 4.4 \times 10^{-4}$ (cgs). The medium between conductors has been taken to be FEP and the corresponding value of thermal conductivity has been used. For those nodal points along the surface the mechanism of transfer includes conduction between interior nodal points and convection and radiation to the surrounding ambient air.

For the multi-cable configuration the two grid networks shown in Figure 2 are proposed. One represents the maximum or extreme condition wherein the only transfer of heat between cables is via radiation, and the cables are infinitesimally separated. The other configuration assumes the cables to be in contact to an extent that is dependent upon a parameter that may be related to the pressure between adjacent cables. When the parameter is unity, the multi-cable configuration is treated as being homogeneous Kapton at the cable-cable interface. A decrease in the parameter below unity is equivalent to including in eq. (2) a thermal contact resistance to the flow of heat between adjacent nodal points.

Due to the relative importance of conduction and radiation in general, it is assumed that the latter configuration will be a much better approximation to the actual conditions, and the results from the former would be expected to be considerably higher. The same basic grid size may be used in the multi-cable configuration as was used for the single cable (the coarse grid). This should speed convergence considerably.



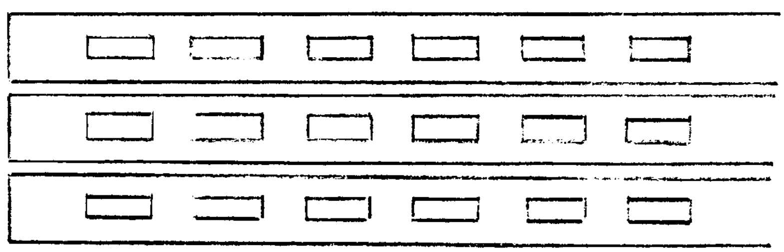


Figure 2: Multiple Cable Finite-Difference Grid Networks

For the single cable configuration, symmetry has permitted consideration of only one quadrant of the cable. The error involved is negligible for the grid size used. For the 3 cable configuration we have symmetry to a first approximation for the coarse grid network. However for more than 3 cables the different surface coefficient of convection on the top and bottom necessitates consideration of one half of the cable, there being only one line of symmetry through the central conductor. This lack of perfect two dimensional symmetry arises due to the 50% difference in the top and bottom surface coefficient of convection.

III. HEAT PRODUCTION AND TRANSFER MECHANISMS

Heat generation: The heat produced in Joulean heating of a conductor of resistivity ρ, cross section A, and length L passing a current I is given by

$$Q = \frac{\rho L}{A} I^2. \qquad [3]$$

In general the resistivity ρ is temperature dependent and for the case of nickel plated copper and for a wide range of temperatures, this temperature dependence should not be neglected. The composite resistivity used in the calculations was calculated from an area weighted sum of the two resistivities. Hence, the heat produced in each conductor was calculated according to the above equation using the temperature of each individual conductor in the calculation of ρ.

Conductive transfer: The internal heat transfer from the uniform temperature conductors to their surroundings will be via conduction. Conduction from the conductors to the surface will be through approximately 1.5×10^{-3} in. of FEP adhesive and 2×10^{-3} in. of Kapton. The heat transfer between two points which differ in temperature by ΔT is given by

$$H = kdA \frac{\Delta T}{\Delta x} \qquad [4]$$

where k is the thermal conductivity of the intervening medium, dA is the element of area through which the heat flows and Δx is the separation of the two points. In general the thermal conductivity is temperature dependent. By taking the values for k at approximately 100°C this temperature dependence has been taken into account to a first approximation without unnecessarily complicating the calculations. For the fine grid the separate thermal conductivities, k_k and k_f, of Kapton and FEP, respectively, have been used in regions where the heat flows in a single medium between two points. For heat flow parallel to an interface the value of conductivity has been taken to be

$$k = (k_K dA_K + k_F dA_F)/(dA_K + dA_F) \quad [5]$$

For the coarse grid, in those regions where the heat flow is through an interface, the value used for k has been a weighted average of the values k_k and k_f.

Convective transfer: Heat is transferred to the air surrounding a heated surface because of a combination of conduction within the fluid and energy transport due to fluid motion. For the case of free convection, the fluid motion arises from density currents produced by the temperature differential between the surface and surrounding air. Such convective heat transfer, H, is found to be given by

$$H = hdA\ (T_o - T_i) \quad [6]$$

where h, the surface coefficient of convection, may be evaluated through the consideration of certain dimensionless parameters known as Nusselt, Prandtl Grashof numbers. The relation for the coefficient h is

$$h = \frac{N_n\ L}{k} \quad [7]$$

where L is a characteristic length, k the thermal conductivity, and N_n is the Nusselt number, which bears the following relation to the Grashof and Prandtl numbers:

vertical plate: $N_n = .59\ (N_p.N_g)^{1/4}$

horizontal surface, top: $N_n = .52\ (N_p.N_g)^{1/4}$

horizontal surface, lower: $N_n = .25\ (N_p.N_g)^{1/4}$

The product $N_p.N_g$ is given by the relation

$$N_p.N_g = \frac{g \beta \rho^2 L^3 \theta C_p}{\mu k} \qquad [8]$$

where g is the acceleration due to gravity, β the fluid volume expansion coefficient, ρ is the fluid density, L is the cable width, θ is the temperature excess, C_p is the specific heat of the fluid, μ is the dynamic viscosity and k is the fluid thermal conductivity. The fluid in the present case is air and the various quantities are to be evaluated at the average of surface and ambient temperatures.

Radiation transfer: The heat transferred via radiation from a surface element dA is given by

$$H = \sigma \epsilon F dA \left(T_o^4 - T_i^4 \right) \qquad [9]$$

where σ is the Stefan-Boltzman constant, ε is the emissivity, and F is a geometry factor expressing the fraction of the emitted radiation which is absorbed. For cases where the emitting surface is enclosed, F may be taken as unity. The value of the emissivity ε for a Kapton surface has been determined by the manufacturer to be 0.70.

IV. PROGRAM DESCRIPTION

The basic assumption underlying the development of the present mathematical model is that the finite difference technique is a sufficient approximation to the solution which would be obtained, were the problem analytically soluble. In this model a small number of difference equations are used to express the net heat flow into the point i (eq. 2), the different equations corresponding to differing external and/or internal boundary conditions for a given nodal point. In this way the continuum of a conducting medium has been replaced by a grid of nodes and the appropriate equation of type (2) is programmed for each nodal point. We thus assume that upon solving equation (2) for T_i we not only obtain the temperature of the point i but also that of the entire rectangle centered around that point. An instruction code number is associated with each nodal point which transfers control of the program to the appropriate finite difference equation for calculation of the temperature of that point. The temperature of a given node is assumed to depend upon that of adjacent surrounding nodes. This temperature is then compared to that computed for the same point during the previous iteration, and the difference is summed in a "residual-sum bucket". The value of the residual sum, Z, gives the total summed residual of all points following each complete iteration. This number is then used as an indication of the degree of convergence of the solution. The nodal temperatures of the finite difference grid are stored in an array T (I,J) and each new temperature replaces that from a previous iteration, thus speeding convergence. In essence, we have effected the solution of a number of simultaneous equations for the temperature by a continuous rather than selective adjustment of the nodal temperature values. Though indirect and inefficient, this method is more readily adaptable to many diverse configurations.

Referring to the PROGRAM LISTING we see that the specification of the boundary location, and the internal and boundary conditions is through the instruction code numbers in the DATA statements and through parameter inputs in the INPUT statement. Initial temperature values are assigned to the nodal points in statements 35 - 55. This assignment is somewhat arbitrary, being based for the case of a single cable on the experimental results. This assignment, though not essential, is found to speed convergence of the solution. The coefficients multiplying the temperature differences for conduction and convection in eq. (2) are assigned in statements 65 - 75. These values are dependent on the geometry chosen for the grid network and must be re-calculated if a grid different than that described herein is desired.

The program described herein will treat cases for a single cable in air or a single cable with the bottom surface held at ambient temperature, T0. For the former case the INPUT parameter L must be 2 and P must be non zero. For the latter case one must INPUT L=3 and P=0. In order to use the program for a single cable in vacuum, and must delete statements 71 - 74 in addition to the numerical portion of statements 80, 81, 83, 89 and 92. Simply as a check on the heat balance for the system, heat input and heat output for the cable have been computed in the quantities H and E, respectively. These calculations in no way affect the nodal temperature and are only intended as another means to ascertain the degree of convergence for the case of a single cable in air. In order for the numbers to be meaningful for the vacuum case, it would be necessary to suppress convection in calculating the quantity E. Experience with the program has shown that one can expect the heat balance discrepancy to be on the order of 2-5% for good convergence.

The dependence of the electrical resistivity on conductor temperature or conductor location is taken into account in statement 154 where the internal heat

generated is calculated for each conductor separately, based upon the temperature of that conductor for the previous iteration.

From lateral symmetry considerations, we need only consider one half of the FCC. As mentioned earlier, we can to a good approximation assume vertical symmetry by using a value for the surface coefficient of convection which is an average of this constant on the top and bottom horizontal surfaces. This approximation is accomplished in the program by instruction code number 13 for those nodal points which are laterally symmetric and by statement number 217 for those nodal points which are symmetric about the horizontal (vertically symmetric). Statement 217 is not executed when P=0, corresponding to the heat sink case where vertical symmetry is absent.

Partial loading of the cable is accomplished by replacing instruction code number 2 with the number 8 in the DATA statement for those conductors which carry zero current. This results in the same type of finite difference equation being used except that Q=0 (statement 155). In order to introduce different current levels in the various conductors, modifications would be necessary.

For all of the results to be presented, the condition used to insure convergence has been the magnitude of the residual sum, Z (statement 251). This condition resulted somewhat arbitrarily from experience with the program by observing the change in all temperature values after an additional 200 - 500 iterations for a given Z. This condition (251) ensures that the summed residual (absolute value) of all nodal temperatures, in comparing with the temperature values from the previous iteration, is less than 0.02°C. Hence the nodal temperatures have approached an "equilibrium" value, wherein the internal and boundary conditions impose no further (significant) changes. This condition

could be relaxed, possibly to $Z<0.2$ if one is only interested in the temperature of the hottest conductor and an accuracy of no more than $\pm 2°C$ is sufficient. This would reduce computer running time considerably.

In order to run the program, one must only supply the input parameters L, G, T0, I1, P. The variable L represents the number of layers in the grid to be taken from the data block. For air and vacuum cases the variable takes the value two. In these cases the values for the third layer come from the symmetry statement (217). For the heat sink case the variable L takes the value three. The variable G is the initial estimate of the temperature of the hottest conductor and must be expressed in units of (°C). The convergence time will be reduced somewhat if the estimate G does not exceed the final value for the hottest temperature. The variable T0 represents the ambient temperature in units of °C and I1 is the conductor current in amperes. The variable P is a control variable which takes the value zero for the heat sink case and any non-zero value for all other cases.

A typical output is shown following the Program Listing where the nodal temperatures are presented sequentially beginning with the first instruction code number and continuing through the grid network by row.

Typical computing times required to meet the indicated convergence requirement, for a machine with a memory cycle of 2 μsec, fall in the range of 30 - 60m. As mentioned previously, this time is dependent on the value chosen for the initial estimate, G.

V. PROGRAM LISTING

```
5  REM PROGRAM FOR CALCULATING THE TEMPERATURE RISE PROFILE IN FCC
10  DIM T[29,3]
20  PRINT "INPUT THE VALUES FOR L,G,TO,I1,P, WHERE L=2 FOR THE SINGLE"
21  PRINT " CABLE IN AIR OR IN VACUO AND L=3 FOR THE CASE OF CONSTANT"
22  PRINT "TEMPERATURE ON ONE SURFACE, G=THE INITIAL ESTIMATE OF THE"
23  PRINT " HIGHEST TEMPERATURE, T0= THE AMBIENT TEMPERATURE, I1= THE"
24  PRINT "CONDUCTOR CURRENT, AND P=0 FOR THE HEAT SINK CASE AND P=1"
25  PRINT "                        FOR ALL OTHER CASES"
26   INPUT L,G,T0,I1,P
30  LET A=49
35  FOR I=1 TO 29
40  FOR J=1 TO L
45  LET T[I,J]=G*(1-EXP(-.7*I))
50  NEXT J
55  NEXT I
60  LET T=0
65  LET H1=3.50000E-05
66  LET V1=3.20000E-03
67  LET H2=9.30000E-05
68  LET V2=5.04000E-03
69  LET H6=4.65000E-05
70  LET V7=2.40000E-03
71  LET S=1.73000E-05*T0
72  LET S9=1.30000E-05*T0
73  LET S0=8.18000E-06*T0
74  LET S2=2.58000E-06*T0
75  LET V0=8.00000E-04
80  LET D0=2*H1+V0+8.18000E-06
81  LET D=2*H1+V1+1.73000E-005
82  LET D2=2*H2+2*V2
83  LET D3=2*H1+V2+1.73000E-05
85  LET D5=2*H2+2*V1
86  LET D6=H6+H2+2*V1
87  LET D7=3*H6+2*V7
89  LET D9=3*H1+V7+1.30000E-05
92  LET E2=2*H6+2*V0+2.58000E-06
110  LET Z=E=H=0
115  FOR J=1 TO L
120  FOR I=1 TO 29
122  LET R=(T0+273)↑4-(T[I,J]+273)↑4
125  READ K
130  IF K=1 THEN 149
131  IF K=2 THEN 154
132  IF K=3 THEN 160
133  IF K=4 THEN 165
134  IF K=5 THEN 170
135  IF K=6 THEN 175
136  IF K=7 THEN 180
137  IF K=8 THEN 185
```

```
138  IF K=9 THEN 190
139  IF K=10 THEN 195
141  IF K=12 THEN 205
142  IF K=13 THEN 210
149  LET R=9.82000E-14*R
150  LET X=(H1*(T[I-1,J]+T[I+1,J])+V1*T[I,J+1]+S+R)/D
151  LET E=E+1.73000E-05*(T0-X)+R
152  GOTO 216
154  LET Q=(4.31800E-04+1.82620E-06*T[I,J])*I1↑2
155  LET X=(H2*(T[I-1,J]+T[I+1,J])+V2*(T[I,J-1]+T[I,J+1])+Q)/D2
156  LET H=H+Q/2
157  GOTO 230
160  LET R=9.82000E-14*R
161  LET X=(H1*(T[I-1,J]+T[I+1,J])+V2*T[I,J+1]+S+R)/D3
162  LET E=E+1.73000E-05*(T0-X)+R
163  GOTO 216
165  LET X=T0
166  GOTO 230
170  LET X=(H2*(T[I-1,J]+T[I+1,J])+V1*(T[I,J-1]+T[I,J+1]))/D5
171  GOTO 230
175  LET X=(H6*T[I-1,J]+H2*T[I+1,J]+V1*(T[I,J-1]+T[I,J+1]))/D6
176  GOTO 230
180  LET X=(2*H6*T[I-1,J]+H6*T[I+1,J]+V7*(T[I,J-1]+T[I,J+1]))/D7
181  GOTO 230
185  LET Q=0
186  GOTO 155
190  LET R=7.36000E-14*R
191  LET X=(2*H1*T[I-1,J]+H1*T[I+1,J]+V7*T[I,J+1]+S9+R)/D9
192  LET E=E+1.30000E-05*(T0-X)+R
193  GOTO 216
195  LET R=3.30000E-14*R
196  LET X=(2*H1*T[I+1,J]+V0*T[I,J+1]+S0+R)/D0
197  LET E=E+8.18000E-06*(T0-X)+R
198  GOTO 216
205  LET R=9.82000E-15*R
206  LET X=(H2*T[I+1,J]+V0*(T[I,J-1]+T[I,J+1])+S2+R)/E2
207  LET E=E+2.58000E-06*(T0-X)+R
208  GOTO 230
210  LET X=T[I-2,J]
211  GOTO 230
216  IF P=0 THEN 230
217  LET T[I,J+2]=X
230  LET Z=Z+ABS(T[I,J]-X)
235  LET T[I,J]=X
240  NEXT I
245  NEXT J
249  RESTORE
250  LET T=T+1
251  IF Z<2.00000E-02 THEN 270
255  IF T>A THEN 270
```

```
265  GOTO 110
270  PRINT "FOR THE VALUES L =";L;"G =";G;"TO =";T0,"I1 =";I1
275  PRINT "THE RESULTS AFTER ";T;"ITERATIONS ARE:"
280  PRINT "RES. SUM=";Z;"HEAT IN=";H;"HEAT OUT=";E
290  FOR J=1 TO L
291  FOR I=1 TO 28
295  PRINT T[I,J];
296  NEXT I
297  PRINT
298  PRINT
301  NEXT J
302  IF Z<2.00000E-02 THEN 600
305  LET A=A+300
310  GOTO 255
400  DATA 10,9,1,3,1,3,1,3,1,3,1,3,1,3,1,3,1,3,1,3,1,3,1,3,1,3,1,3,13
401  DATA 12,7,6,2,5,2,5,2,5,2,5,2,5,2,5,2,5,2,5,2,5,2,5,2,5,2,5,2,13
402 DATA    4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4
600  END

FOR THE VALUES L = 2    G = 65    TO = 23     I1 = 3
THE RESULTS AFTER  50   ITERATIONS ARE:
RES. SUM= .297546    HEAT IN= 2.98825E-02   HEAT OUT=-3.17247E-02
 36.5282        37.9836        45.8924        58.9902        55.8748        64.5479
 59.0066        66.4565        60.1242        67.1523        60.5338        67.4079
 60.6844        67.502         60.7397        67.5365        60.7601        67.5492
 60.7676        67.5539

 36.582         38.033         46.0274        59.3193        56.0507        64.9046
 59.2001        66.8203        60.323         67.5185        60.7346        67.775
 60.8858        67.8694        60.9415        67.9041        60.9619        67.9168
 60.9695        67.9216

FOR THE VALUES L = 2    G = 65    TO = 23     I1 = 3
THE RESULTS AFTER  350  ITERATIONS ARE:
RES. SUM= 3.41797E-02   HEAT IN= 2.99547E-02   HEAT OUT=-3.22529E-02
 35.9537        37.4112        45.5401        59.2189        56.3995        65.4365
 59.8145        67.382         60.8803        67.9894        61.2147        68.1822
 61.3222        68.2454        61.3581        68.2671        61.3706        68.2747
 61.3752        68.2776

 36.0084        37.4626        45.6819        59.5459        56.5765        65.7906
 60.0109        67.7448        61.0828        68.3549        61.4191        68.5485
 61.5271        68.612         61.5633        68.6338        61.5758        68.6414
 61.5804        68.6443

FOR THE VALUES L = 2    G = 65    TO = 23     I1 = 3
THE RESULTS AFTER  433  ITERATIONS ARE:
RES. SUM= 1.98669E-02   HEAT IN= 2.99592E-02   HEAT OUT=-3.22896E-02
 35.9623        37.4208        45.5548        59.2403        56.4269        65.4732
 59.8548        67.4297        60.9276        68.041         61.2631        68.2329
 61.3691        68.2943        61.4034        68.3146        61.4149        68.3215
 61.419         68.3239

 36.0171        37.4723        45.6966        59.5674        56.6039        65.8273
 60.0512        67.7925        61.1301        68.4065        61.4675        68.5993
 61.5741        68.661         61.6087        68.6814        61.6202        68.6883
 61.6243        68.6907
```

VI. RESULTS

The temperature rise profile for a single cable in air and in vacuum as a function of conductor current and conductor location, for all conductors under the same current load as well as for partial loading of the conductors, has been obtained. Comparison is made with the experimental results where available.

The result for the temperature rise profile in a single cable in air is shown in Figure 3 plotted as a function of conductor number. All conductors were equally loaded at a current level of three amperes. It can be seen that the decrease in temperature near the end of the cable is more pronounced and more rapid when compared to experiment. This could result from the failure to consider the temperature dependence of the thermal conductivity of Kapton as well as that of the convection coefficient, h. Only one half of the conductor is shown because of symmetry. Results are shown for both the fine and coarse grids and it can be seen that the two agree to within 3°C and this is possibly due to the different convergence requirements used for the two calculations. Hence for all practical purposes, the two grids agree and one is justified in using the coarse grid in the interest of computer time.

The results for the temperature rise in the hottest conductor of a single cable in air are presented in Figure 4 as a function of the conductor current. The experimental result is higher for low currents but does not rise as rapidly as the theoretical calculations. This may be due to slight inaccuracies in the resistivities and coefficients of resistivity of copper and nickel, the values used being taken from the CRC Handbook of Tables for Applied Engineering Science. This phenomenon could also result from the way in which the temperature dependence of the thermal conductivities has been treated in the formulation. Similar results are shown in Figure 5 for the case of vacuum surroundings.

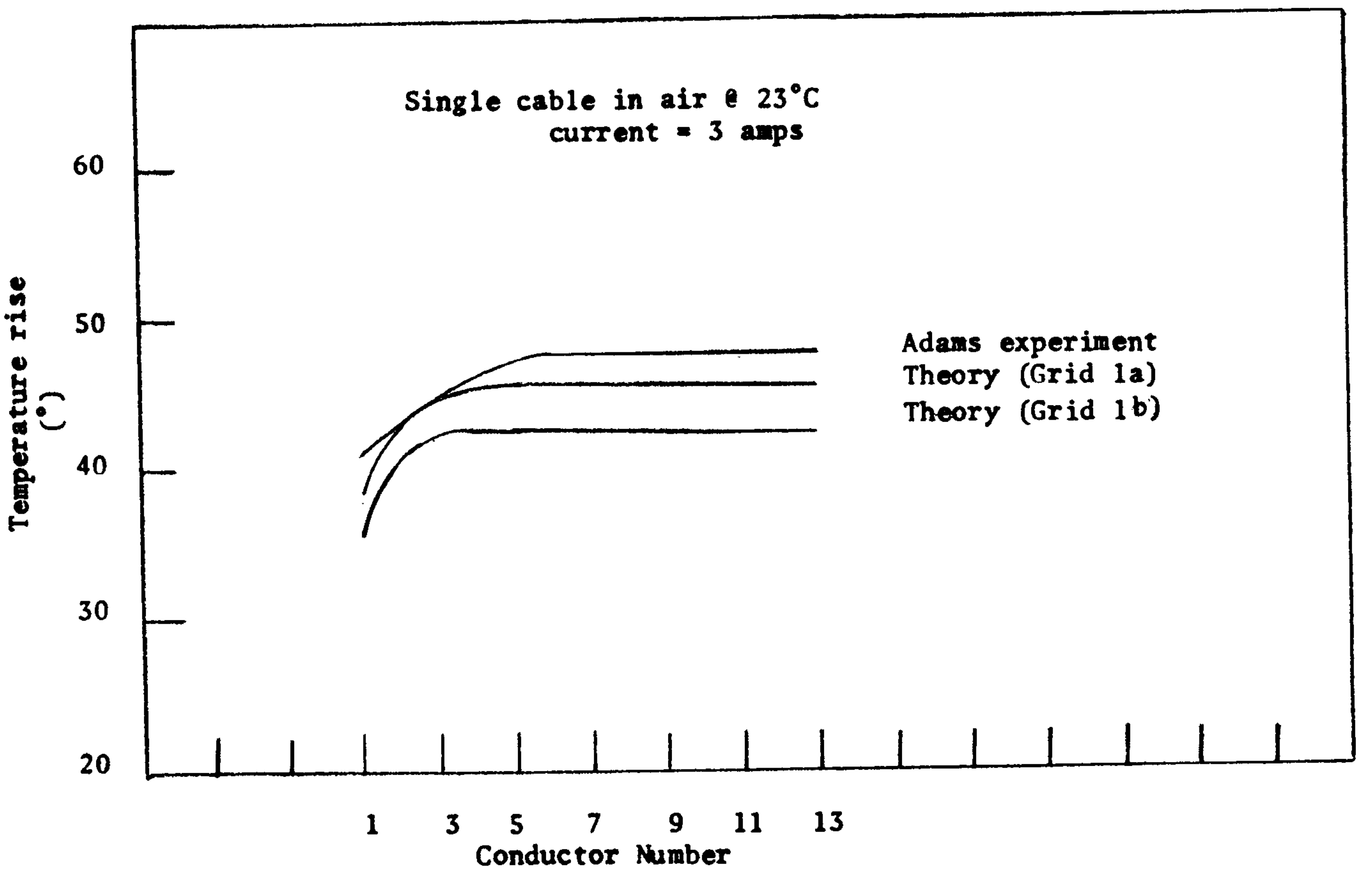


Figure 3: Temperature Rise vs. Conductor Number

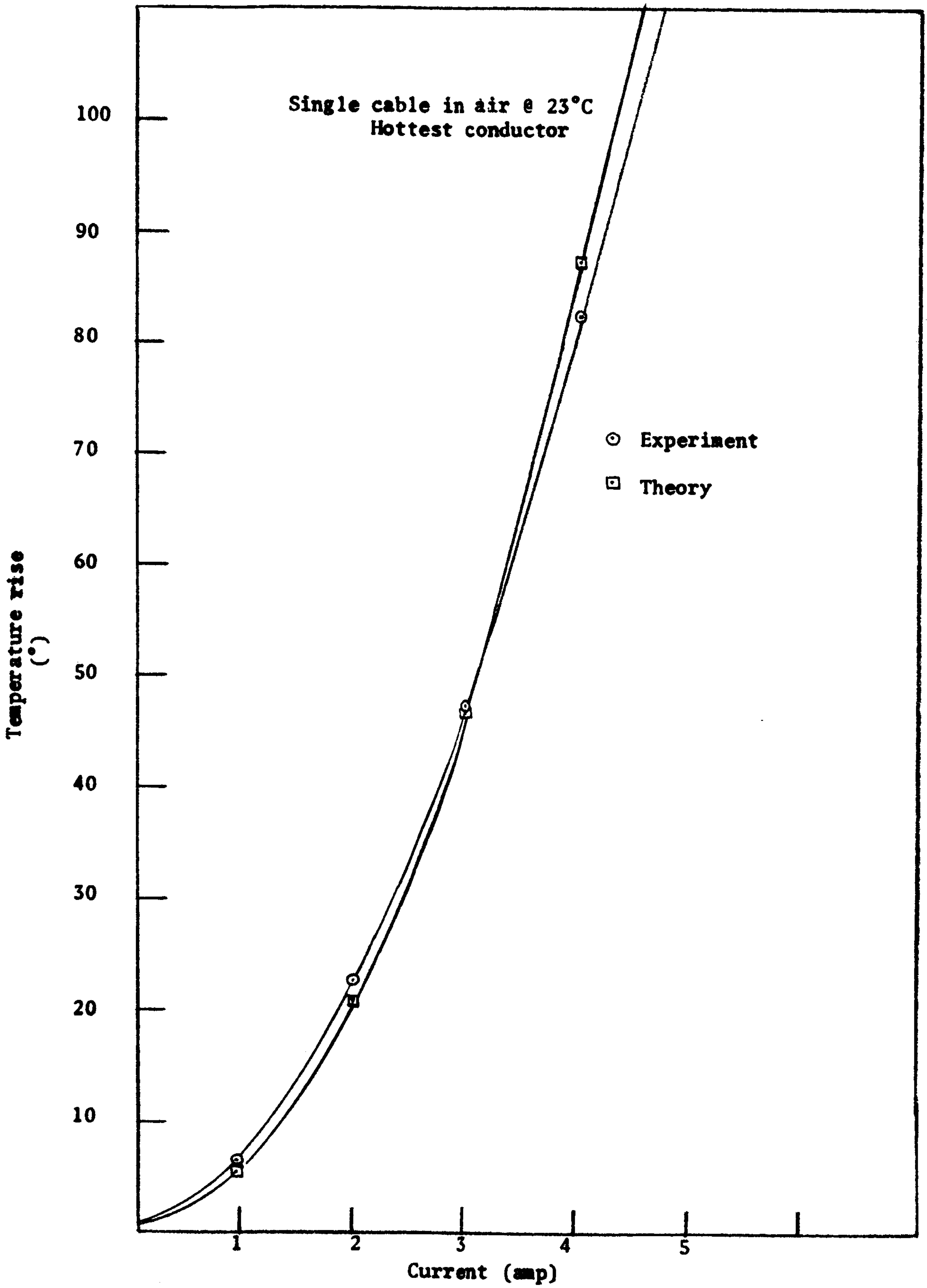


Figure 4: Temperature Rise (air) vs. Current

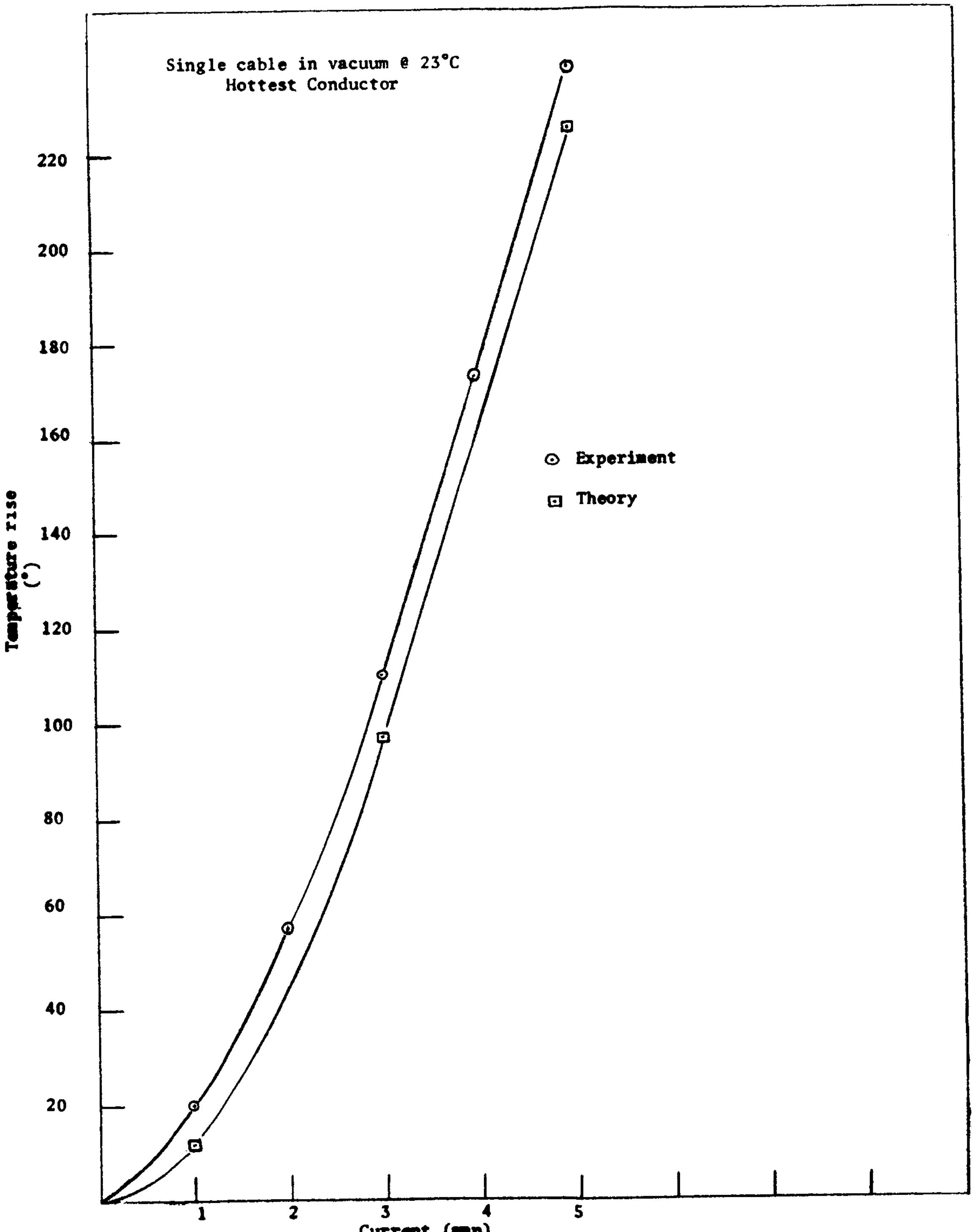


Figure 5: Temperature Rise (vacuum) vs. Current

Calculations have been made for the case of a single cable with the top and vertical surfaces subjected to free convection and the bottom surface in thermal contact with a heat sink. It has been assumed that the adhesive used to attach the cable surface to the heat sink has the following properties:

thermal conductivity, $k = 4 \times 10^{-4}$ (cgs)

film thickness, $1 = 3.5 \times 10^{-3}$ in.

These are typical of contact adhesives. The results are shown in Figure 6 with the temperature rise plotted as function of conductor current, assuming all conductors to carry the same current. Due to the presence of the heat sink, the results are applicable to any conductor in the cable. Also presented are the results without an adhesive, assuming the bottom surface to be held at ambient temperature (23°C).

Results similar to those in Figure 4 have been obtained for the configuration of current loading on the central seventeen (17) conductors and the temperature of the hottest conductor is no more than three degrees lower than that under full cable load. However the temperature profile near the first loaded conductor is somewhat more pronounced than in the case of a full load. The effect of a change in the number of loaded conductors while maintaining a constant current is presented in Figure 7.

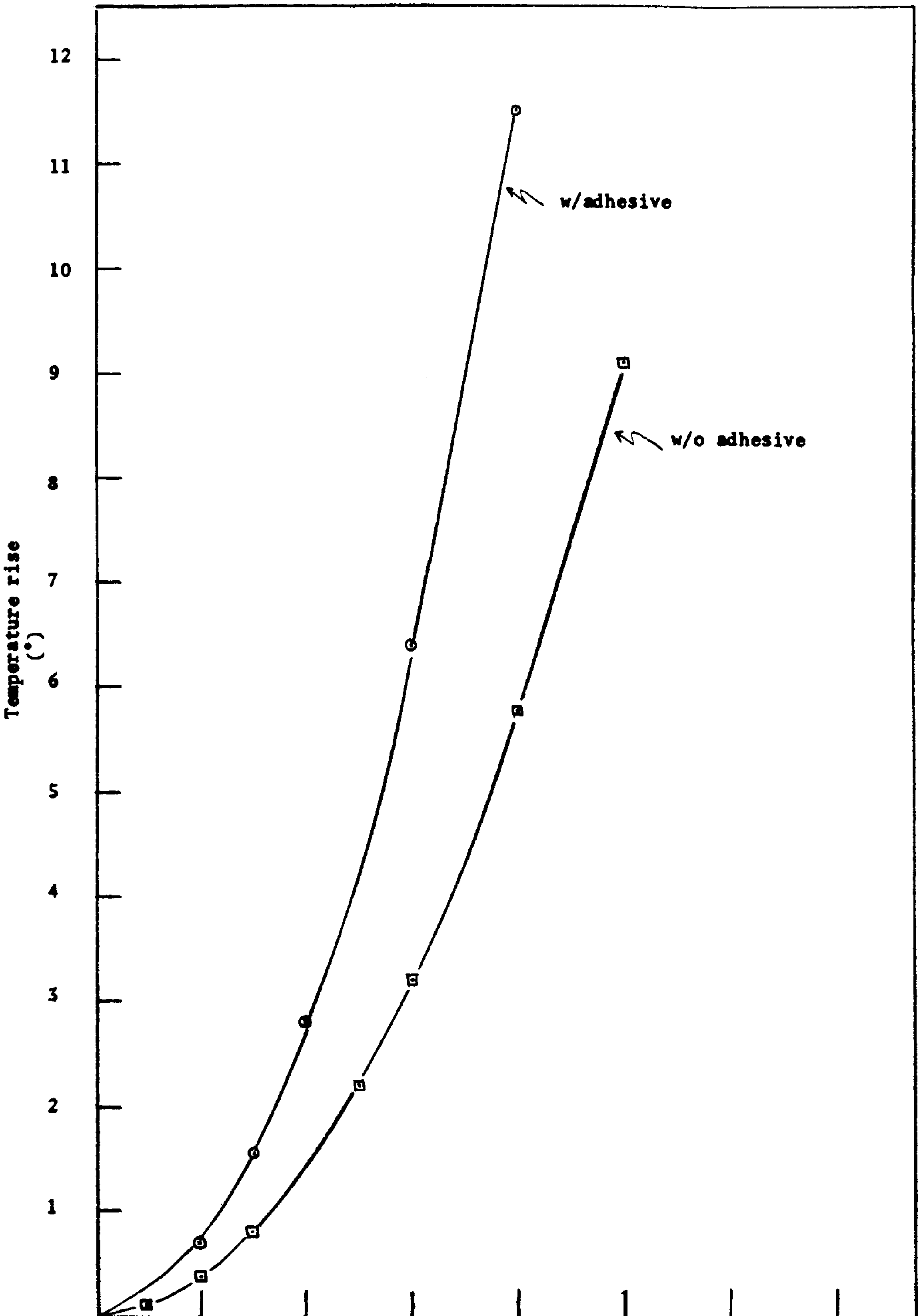


Figure 6: Temperature Rise vs. Current for Heat Sink Case

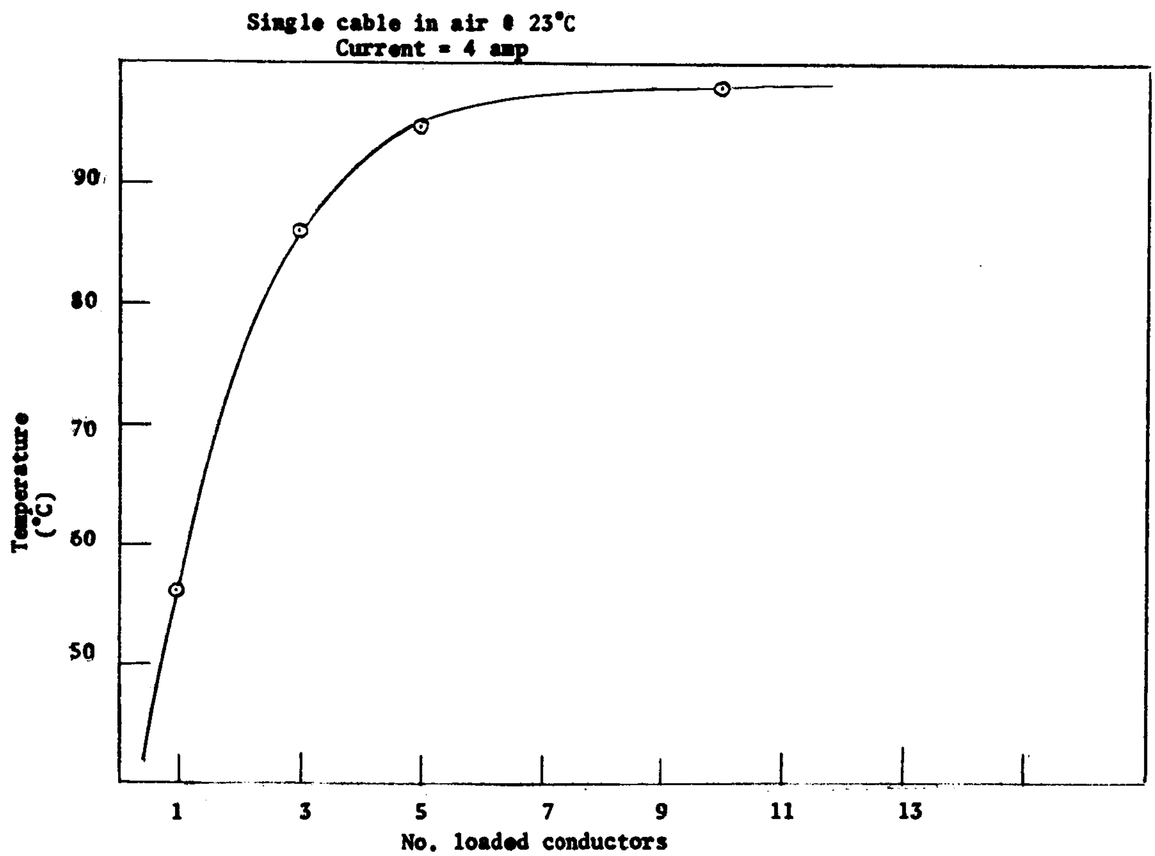


Figure 7: Temperature Rise vs. Number of Loaded Conductors

VII. CONCLUSION

The finite-difference iterative technique, using a rather large grid network, has resulted in good agreement with the experimental results for a single cable in air and in vacuum. The technique could be modified rather easily for the case of a random current distribution within the cable.

Though the results presented are for a single cable, the technique employed should also be applicable to multiple cable networks after investigation of the heat transfer characteristics at the cable-cable interface. In this regard, the concept of thermal contact resistance mentioned earlier seems to hold much potential. Also worthy of consideration is the assumption of infinitesimally separated cables, transferring heat via radiation and conduction through the intervening air. It may be that the aggregation of these two approaches would be most fruitful and would result in a close approximation to the actual conditions within a multi-cable configuration.

Results indicate that little value is gained from partial loading unless the number of conductors void of current is near the maximum number of conductors in the cable. For applications requiring a minimum number of conductors, it may be desirable to use a smaller cable.

The most encouraging of the results is that for the cable in thermal contact with a heat sink. From these results we find, as one would expect, that at points where the cable is in contact with the heat sink much higher current levels are tolerable before excessive temperatures are encountered. The limiting factor then becomes the cable harness leading from the current source to the cable. This limitation could be reduced by enclosing the harness with a good thermally conducting braid attached to a heat sink at various points along the braid.

It would be of interest to investigate the results for a multi-cable configuration attached to a heat sink. It may result that such a configuration attached to a heat sink at intervals along the network would allow current levels approaching that of a single cable in air.

ELECTRICAL IMPEDANCE OF FCC

By Dr. Yiu Sing Liu
John C. Calhoun State Tech. Jr. Col.

PERIODICAL CURRENT AND VOLTAGE
PROPAGATION ON FLAT CONDUCTOR CABLE

ABSTRACT

The electrical characteristics of flat conductor cables (FCC) are investigated in the context of multiple transmission lines theory. Analytical expressions for the coefficients of capacitance of conductors in a single cable are obtained. Numerical values calculated with these expressions are in good agreement with experimental data. Crosstalk, attenuation constants and phase angles of the current and voltage in flat conductor cable are also calculated.

I. INTRODUCTION

Due to the close proximity of conductors in flat cable, the capacitive and inductive coupling between conductors are very strong. Therefore, the electrical characteristics of FCC should be investigated in the context of multiple transmission line theory. In the NASA TMX-53975 Report: "Flat Conductor Cable Design, Manufacture, and Installation", the distinction between wave propagation in a pair of transmission lines and that in multiple transmission lines is not clearly drawn. The failure of making this distinction leads to two major errors.

The first error is related to capacitance. It is found that the values in Tables 3-3 through 3-7 in the NASA TMX-53975 Report are actually coefficients of capacitance. The failure to understand this, the author believes may contribute to the large deviations of the values in these tables. In the present report the concepts of coefficients of capacitance and **inductance** are examined carefully, and analytical expressions for these quantities are derived. Some aspects of the measurement of coefficient of capacitance are also discussed.

The second error is related to impedance. In the NASA TMX-53975 Report, the characteristic impedance of transmission-line pair

$$Z_0 = \frac{\sqrt{R^2 + 4\pi^2 f^2 L^2}}{\sqrt{G^2 + 4\pi^2 f^2 C^2}} \qquad [1]$$

is adapated for FCC calculation. This is clearly invalid. On multiple trans-

mission lines, there are in general, n modes of wave propagation on each conductor and associated with each mode is a distinct value of "impedance". There is no single value of characteristic impedance for a pair of conductors in FCC. In this report the multiple transmission line theory, which has been developed since 1930's, is invoked to investigate the electrical characteristics (eg, attenuation constant, phase angle and crosstalk) of flat conductor cable.

II. COEFFICIENTS OF CAPACITANCE

A. The Concept of Coefficients of Capacitance

Let us consider a system of n conductors and designate the charge and potential on the i^{th} conductors as Q_i and V_i, respectively (Figure 1). Applying the principle of superposition, we may express the charge on the i^{th} conductor due to the potentials on all conductors as

$$Q_i = C_{i1}V_1 + C_{i2}V_2 + \cdots\cdots + C_{in}V_n \quad \text{for} \quad i = 1, 2, \cdots\cdots n$$

$$\text{or} \quad Q_i = \sum_{j=1}^{n} C_{ij} V_j \quad \text{for} \quad i = 1, 2, \cdots\cdots n. \qquad [2]$$

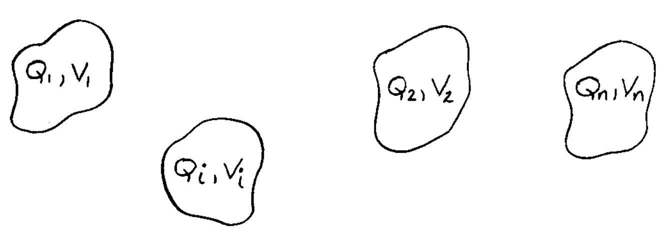


Figure 1: A system of n conductors charged to different potentials.

The coefficients $C_{i,j}$ are called coefficients of capacitance when $i \neq j$, and C_{ii} is called self-capacitance of the i^{th} conductor. The value of $C_{i,j}$ depends not only on the i^{th} and j^{th} conductors but on all conductors in the cable.

To illustrate the relation between the coefficients of capacitance and the capacitance commonly used for a two-body system, let us consider a parallel plate capcitor. For a two-body system equations(2) reduce to

$$Q_1 = C_{11}V_1 + C_{12}V_2$$

and

$$Q_2 = C_{21}V_1 + C_{22}V_2 . \qquad [3]$$

The capacitance of a two-body system is defined as

$$C = \frac{Q_1}{V_1 - V_2} = \frac{-Q_1}{V_1 - V_2} , \qquad [4]$$

and solving equations (3) and (4) leads to

$$C = \frac{C_{11}C_{22} - C_{12}C_{21}}{C_{11} + C_{12} + C_{21} + C_{22}} . \qquad [5]$$

Since the two conductors are identical,

$$C_{11} = C_{22}$$

and

$$C_{12} = C_{21} .$$

Furthermore, since $Q_1 = - Q_2$ [6]

and $C_{11} = C_{12}$,

equation (5) becomes

$$C = C_{11} = -C_{12}. \qquad [7]$$

It can be shown that Equation 6, also holds for spherical capacitors and for cylindrical capacitors. Thus for common two-body capacitors, total capacitance is the same as coefficient of capacitance. However, this is not true for a multiple conductor system.

To investigate the physical meaning of coefficients of capacitance, let us introduce two column matrices $\underset{\sim}{V}$ and $\underset{\sim}{Q}$, and a square matrix $\underset{\approx}{C}$ where

$$\underset{\sim}{V} = \begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{pmatrix}, \qquad [8a]$$

$$\underset{\sim}{Q} = \begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_i \\ \vdots \\ Q_n \end{pmatrix}, \qquad [8b]$$

and

$$\underset{\approx}{C} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & \cdots\cdots & C_{1n} \\ C_{21} & C_{22} & C_{23} & \cdots\cdots & \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ C_{n1} & C_{n2} & C_{n3} & \cdots\cdots & C_{nn} \end{pmatrix}. \qquad [8c]$$

Using these notations the set of simultaneous linear equations in Equation (2) can be expressed in a matrix form,

$$\underset{\sim}{Q} = \underset{\approx}{C}\,\underset{\sim}{V} . \qquad [9]$$

Assume that all conductors except the i^{th} one is grounded and the potential on the i^{th} conductor is one volt

i.e.

$$\underset{\sim}{V} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{pmatrix} . \qquad [10]$$

Substituting this column matrix in Equation (9) and carrying out the matrix multiplication, we have

$$\begin{pmatrix} Q_1 \\ Q_2 \\ \vdots \\ Q_{i-1} \\ Q_i \\ Q_{i+1} \\ \vdots \\ Q_n \end{pmatrix} = \begin{pmatrix} C_{i1} \\ C_{i2} \\ \vdots \\ C_{i\,i-1} \\ C_{ii} \\ C_{i\,i+1} \\ \vdots \\ C_{in} \end{pmatrix} . \qquad [11]$$

Thus we can compute the coefficient of capacitance $C_{i,j}$ by calculating the induced charge on the j^{th} conductor due to a potential of 1 volt on the i^{th} conductor.

B. The Coefficients of Capacitance $C_{i,j}$ of the Conductors at the Center of a Single Cable.

1. Statement of Problem

The problem of calculating the induced charge on the i^{th} conductor due to a potential of 1 volt on the j^{th} conductor is a standard electrostatic problem. The Laplace equation,

$$\nabla^2 V(x,y) = 0, \qquad [12]$$

is first solved for the potential V(X,Y) subject to the boundary conditions as indicated in Figure 2. The gradient of V(X,Y) at the surface of the conductor is proportional to the surface charge density. Integration of the surface charge density over the entire surface of the conductor gives the total induced charge on that conductor and, thus, the coefficient of capacitance.

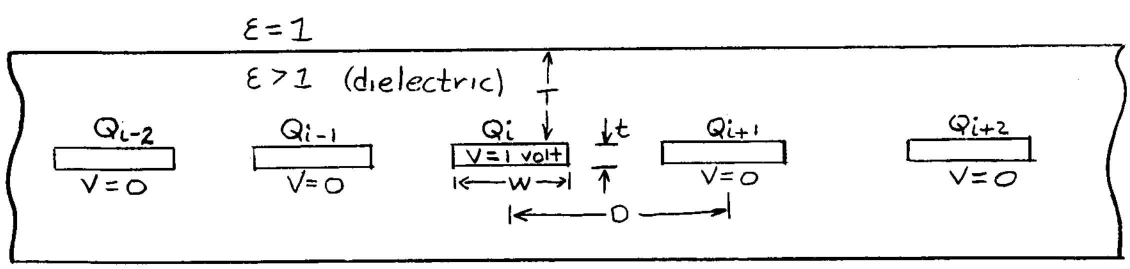


Figure 2. Configuration of Unshielded Flat Cable of Conductors of Finite Thickness

The solution to the Laplace equation subject to the complicated boundary conditions specified in Figure 2 is intangible. Fortunately, since the thickness of the conductor is very small compared with the width of the conductor

$(t/w \leq .1)$, we can assume that the conductors have zero thickness (Figure 3) without introducing appreciable error. The validity of this approximation is verified by the good agreement of the results computed using the present theory with the experimental data reported in NASA TMX-53975 report.

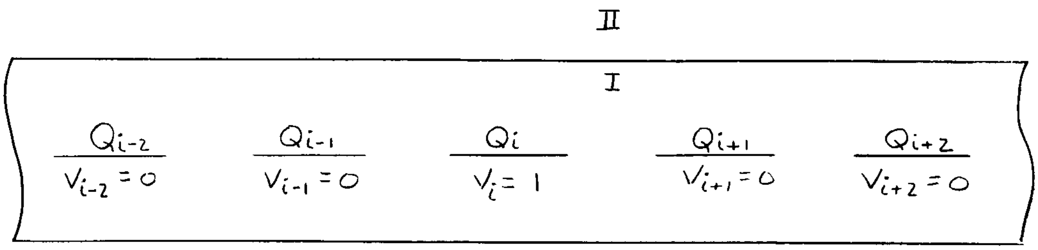


Figure 3. Configuration of Unshielded Flat Cable of Conductors of Zero Thickness

2. Boundary Conditions

Together with the assumption of zero conductor thickness, the potential along the x-axis is assumed to be a linear function of x (i.e., the electric field is constant) in the two areas adjacent to the j^{th} conductor and zero for $|x| > D-\frac{w}{2}$.

i.e.

$$V(x,0) = f(x) = \begin{cases} 1 \text{ Volt} & \text{for } 0 \leq x \leq w/2 \\ \dfrac{d - w/2 - x}{d-w} & \text{for } w/2 < x < d - w/2 \\ 0 & \text{for } x \geq d - w/2 \end{cases} \qquad [13]$$

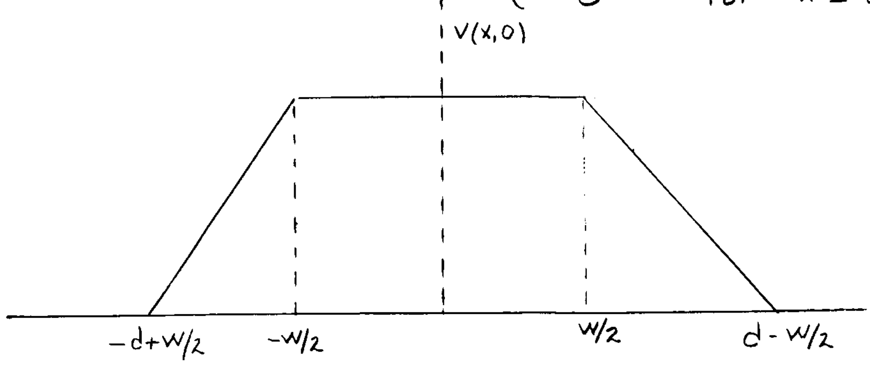


Figure 4. The Potential along y=0

In addition, V(X,Y) also satisfies the following boundary conditions:

$$V(x,0) = V(-x,0), \qquad [14]$$

$$\lim_{x\to\infty} V(x,y) = \lim_{y\to\infty} V(x,y) = 0, \qquad [15]$$

$$V_{I}(x,t) = V_{II}(x,t), \qquad [16]$$

and

$$\varepsilon_1 \frac{\partial}{\partial y} V_{I}(x,y)\Big|_{y=T} = \varepsilon_2 \frac{\partial}{\partial y} V_{II}(x,y)\Big|_{y=T} \qquad [17]$$

where I and II indicate, respectively, regions I and II, and Equation (16) & (17) represent the continuity conditions of potential and the Y-component of electric field at the surface of the dielectric.

3. Solutions

The solution of Laplace's equation (equation 12) in region I is expressed in terms of Fourier integral (Appendix I):

$$V_{I}(x,y) = \frac{2V_o}{\pi(d-w)} \int_0^\infty \frac{\cos\alpha\, w/2 - \cos\alpha(d-w/2)}{\alpha^2} \frac{1}{1+\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}} \times \left[e^{-\alpha y} + \frac{\varepsilon-1}{\varepsilon+1} e^{-2\alpha t} e^{\alpha y}\right] \cos\alpha x \, d\alpha \qquad [18]$$

where V_o is the potential on the j^{th} conductor, for convenience chosen to be 1 volt, and ε is the dielectric constant which is equal to one for air. Invoking Gauss' law, the surface charge density on the conductor is related to

partial derivative of V(X,Y) with respect to Y through the following equation:

$$\sigma(x) = -2\varepsilon\varepsilon_0 \frac{\partial}{\partial y} V(x,y)\bigg|_{y=0} . \qquad [19]$$

Substituting equation (18) into equation (19) gives

$$\sigma(x) = \frac{4V_0\varepsilon}{\pi(d-w)} \int_0^\infty \frac{\cos\alpha w/2 - \cos\alpha(d-w/2)}{\alpha^2} \frac{-1+\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}}{1+\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}} \cos\alpha x \, d\alpha . \qquad [20]$$

Integrating $\sigma(x)$ from $-w/2$ to $w/2$ gives the total charge on the j^{th} conductor, or the self capacitance.

$$Q_\gamma = C_{\gamma,\gamma}$$

$$= 2\int_0^{w/2} \sigma(x)\,dx$$

$$= \frac{8\varepsilon_0\varepsilon_1}{\pi(d-w)} \int_0^\infty \frac{\cos\alpha w/2 - \cos\alpha(d-w/2)}{\alpha^2} \frac{-\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}+1}{\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}+1} \sin\alpha w/2 \, d\alpha , \qquad [21]$$

Similarly,

$$Q_{\gamma+1} = C_{\gamma,\gamma+1}$$

$$= \int_{d-w/2}^{d+w/2} \sigma(x)\,dx$$

$$= \frac{4\varepsilon_0\varepsilon_1}{\pi(d-w)} \int_0^\infty \frac{\cos\alpha w/2 - \cos\alpha(d-w/2)}{\alpha^2} \frac{-\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}+1}{\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}+1} \left[\sin\alpha(d-w/2) + \sin\alpha(d+w/2)\right] d\alpha , \qquad [22]$$

$$Q_{\gamma+2} = C_{\gamma,\gamma+2}$$

$$= \int_{2d-w/2}^{2d+w/2} \sigma(x)\,dx$$

$$Q_{\gamma+2} = \frac{4\varepsilon_0\varepsilon_1}{\pi(d-w)} \int_0^{\infty} \frac{\cos\alpha \frac{w}{2} - \cos\alpha(d-\frac{w}{2})}{\alpha^2} \; \frac{-\frac{\varepsilon-1}{\varepsilon+1} e^{-2\alpha t}+1}{\frac{\varepsilon-1}{\varepsilon+1} e^{-2\alpha t}+1} \left[-\sin\alpha(2d-\tfrac{w}{2}) + \sin\alpha(2d+\tfrac{w}{2})\right] d\alpha \qquad [23]$$

and

$$Q_{\gamma+3} = C_{\gamma,\gamma+3}$$

$$= \int_{3d-\frac{w}{2}}^{3d+\frac{w}{2}} \sigma(x)\, dx$$

$$= \frac{4\varepsilon_0\varepsilon_1}{\pi(d-w)} \int_0^{\infty} \frac{\cos\alpha \frac{w}{2} - \cos\alpha(d-\frac{w}{2})}{\alpha^2} \; \frac{-\frac{\varepsilon-1}{\varepsilon+1} e^{-2\alpha t}+1}{\frac{\varepsilon-1}{\varepsilon+1} e^{-2\alpha t}+1} \left[-\sin\alpha(3d-\tfrac{w}{2}) + \sin\alpha(3d+\tfrac{w}{2})\right] d\alpha, \qquad [24]$$

where

$$\frac{8\varepsilon_0}{\pi} = 6.85 \times 10^{-12} \ \frac{\text{Farad}}{\text{Ft}}$$

According to the potential function assumed in Figure 4, Equations (21) to (24) are valid for all conductors except the two at the edges of the cable.

C. Coefficients of Capacitance, $C_{i,j}$, of conductors at the Edge of a Single Cable.

A conductor at the edge of a flat cable has an environment different from conductors at the center of a cable. Therefore, we expect the coefficients of capacitance, $C_{1,i+j}$ are different from $C_{i,i+j}$ (for $i > 1$). (Actually, it is obvious that the self-capacitance of the conductor at the edge of a cable is smaller than the self-capacitance of other conductors in the cable.)

To calculate the coefficients of capacitance of the conductor at the edge of a cable, let us assume that the potential of this conductor is 1 volt and the rest of the conductor is grounded. (Figure 6)

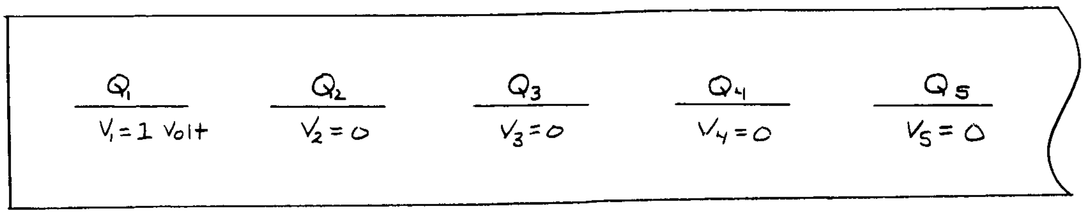


Figure 6. Schematic Diagram of Conductors at the Edge of a Flat Conductor Cable

Assuming that an observer looking from the left of the first conductor sees a dipole and that the electric field between the first and second conductor is constant, the potential at Y=0, V(X,0), **has the following form:**

$$V(x,0) = \begin{cases} w^2/x^2 & \text{for } x < -w \\ 1 & \text{for } -w \le x \le 0 \\ \dfrac{d-w-x}{d-w} & \text{for } 0 < x < d-w \\ 0 & \text{for } x \ge d-w \end{cases}$$

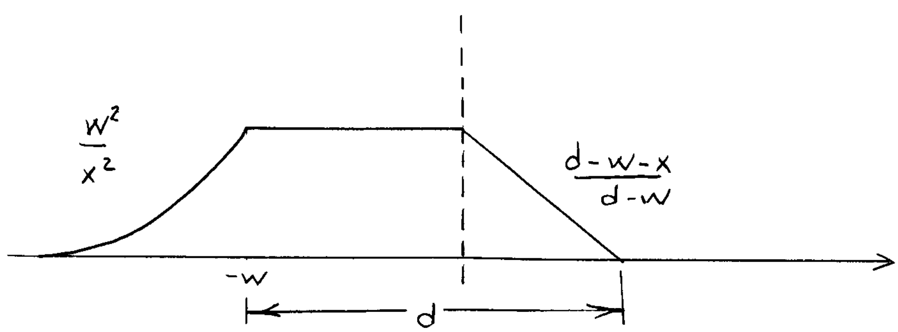


Figure 7: The potential at Y=0 when the conductor at the edge of the cable has a potential of 1 volt.

Using this potential, the coefficients of capacitance can be expressed as the following:

$$Q_1 = C_{1,1}$$

$$= \frac{2\varepsilon_0}{\pi}\int_0^\infty \left\{ \frac{C(\alpha)}{\alpha}(\cos\alpha w - 1) + \frac{D(\alpha)\sin\alpha w}{\alpha} \right\}\left(1 - \frac{\varepsilon - 1}{\varepsilon + 1} e^{-2\alpha t}\right) d\alpha, \qquad [25]$$

$$Q_2 = C_{1,2}$$

$$= \frac{2\varepsilon_0}{\pi}\int_0^\infty \left\{ \frac{C(\alpha)}{\alpha}\left[\cos\alpha(d-w) - \cos\alpha d\right] + \frac{D(\alpha)}{\alpha}\left[\sin\alpha d - \sin\alpha(d-w)\right]\right\}\left(1 - \frac{\varepsilon - 1}{\varepsilon + 1} e^{-2\alpha t}\right) d\alpha, \qquad [26]$$

$$Q_3 = C_{1,3}$$

$$= \frac{2\varepsilon_0}{\pi}\int_0^\infty \left\{ \frac{C(\alpha)}{\alpha}\left[\cos\alpha(2d-w) - \cos\alpha 2d\right] + \frac{D(\alpha)}{\alpha}\left[\sin\alpha 2d - \sin\alpha(2d-w)\right]\right\}\left(1 - \frac{\varepsilon - 1}{\varepsilon + 1} e^{-2\alpha t}\right) d\alpha, \qquad [27]$$

and

$$Q_4 = C_{14}$$

$$= \frac{2\varepsilon_0}{\pi}\int_0^\infty \left\{ \frac{C(\alpha)}{\alpha}\left[\cos\alpha(3d-w) - \cos\alpha 3d\right] + \frac{D(\alpha)}{\alpha}\left[\sin\alpha 3d - \sin\alpha(3d-w)\right]\right\}\left(1 - \frac{\varepsilon - 1}{\varepsilon + 1} e^{-2\alpha t}\right) d\alpha, \qquad [28]$$

where

$$C(\alpha) = \frac{1}{1 + \frac{\varepsilon - 1}{\varepsilon + 1} e^{-2\alpha t}} \left\{ w^2 \int_{-\infty}^{-w} \left[\frac{\sin\alpha x}{x^2}\right] dx - \frac{\cos\alpha(d-w) - \cos\alpha w}{\alpha} - \right.$$

$$\left. \frac{1}{(d-w)\alpha^2}\left[\sin\alpha(d-w) - \alpha(d-w)\cos\alpha(d-w)\right]\right\} \qquad [29]$$

and

$$D(\alpha) = \frac{1}{1 + \frac{\varepsilon - 1}{\varepsilon + 1} e^{-2\alpha t}} \left\{ w^2 \int_{-\infty}^{-w} \left[\frac{\sin\alpha x}{x^2}\right] dx + \frac{\sin\alpha(d-w) + \sin\alpha w}{\alpha} - \right.$$

$$\left. \frac{1}{(d-w)\alpha^2}\left[\cos\alpha(d-w) + \alpha(d-w)\sin\alpha(d-w) - 1\right]\right\} \qquad [30]$$

In the derivation of Equations (21) to (30) for conductors in a flat cable, we make the assumption of zero conductor thickness and constant electric field in the area adjacent to the conductor maintained at a voltage of 1 volt. These two assumptions are invalid for a stack of cables or a cable mounted to a grounded metal surface, because in these two cases the electric field is confined in a region of a thickness of the same order of magnitude as that of the conductor, and these assumptions will alter the electric field significantly.

D. Numerical results and comparison with experimental data

A computer program (Appendix II) is developed for Equations (18) - (21) for computation of self capacitance and coefficients of capacitance. Values of C_{ij} are computed for several conductor configurations and tabulated in Tables 1 and 2.

The quantities C_8, C_{10}, and C_{14} are taken from Tables 3-3 and 3-4 in NASA TMX-53975 Report and are in good agreement with the values of $C_{j,\ j+1}$, $C_{j,\ j+2}$, and $C_{j,\ j+3}$, respectively. However, the values of C_{14} are consistently higher than the values calculated with the present theory. By eliminating the capacitance between the conductors being measured and the environment, the data obtained by the author are in good agreement with the calculated values. (The measured values of $C_{j,\ j+3}$ falls between .13 pf and .23 pf.)

TABLE I. COEFFICIENTS OF CAPACITANCE FOR A SINGLE MYLAR INSULATED AND UNSHIELDED FLAT CABLE (ε_1 = 2.5)

Conductor Width W (mils)	Center-Center Spacing D (mils)	C_{jj} (pF/ft)	$C_{j,j+1}$ (pF/ft)	C_8 (pF/ft)	$C_{j,j+2}$ (pF/ft)	C_{10} (pF/ft)	$C_{j,j+3}$ (pF/ft)	C_{14} (pF/ft)
40	50	20.41	-8.72	7.6-10.3	-.81	.6-.8	-.24	.3-.5
40	75	11.27	-4.87	4.3-5.7	-.35	.5-.7	-.15	.2-.4
65	75	23.08	-10.22	8.0-10.6	-.67	.6-.8	-.21	.3-.5
65	100	13.34	-5.79	4.8-6.2	-.39	.6-.8	-.14	.3-.5

TABLE II. COEFFICIENTS OF CAPACITANCE FOR H-FILM/FEP INSULATED FLAT CABLE (ε_1 = 3.1)

Conductor Width W (mils)	Center-Center Spacing D (mils)	$C_{j,j}$ (pF)	$C_{j,j+1}$ (pF)	C_8 (pF)	$C_{j,j+2}$ (pF)	C_{10} (pF)	$C_{j,j+3}$ (pF)	C_{12} (pF)
40	50	25.07	-10.87	8.5-11.4	-.96	.6-.9	-.26	.3-.6
40	75	13.67	-6.04	4.6-6.1	-.38	.5-.8	-.16	.2-.4
65	75	28.15	-12.68	8.9-11.8	-.74	.6-19	-.21	.3-.6
56	100	15.97	-7.10	5.6-6.6	-.41	.7-.9	-.14	.3-.6

E. Some Aspects on the Measurement and Computation of Coefficients of Capacitance.

(1) In Appendix II we prove that a capacitance bridge measures the coefficients of capacitance when all conductors in the cable other than the pair being measured are grounded. If some of the conductors are not grounded, the value registered on the bridge will neither be the coefficient of capacitance, nor the total capacitance.

(2) The self-capacitance of a conductor can be measured by connecting that conductor to one pole of the capacitance bridge and the remaining conductors to another pole. This follows the fact that the sum of the induced charges of all grounded conductor is equal to the positive charge on the conductor maintained at a potential of 1 volt, i.e.,

$$\sum_{\substack{i=1 \\ i \neq j}}^{n} C_{ij} = C_{jj} \qquad [31]$$

Equation (31) is satisfied by the calculated values in Tables 1 and 2 within 3%.

(3) The coefficients of capacitance between the conductors at the edge of the cable are not the same as the corresponding ones at the center of the cable. For example,

$$C_{1,1} < C_{j,j} \quad \text{for } j \neq 1 \qquad [32]$$

(4) Since the values of $C_{i,i+2}$ and $C_{i,\ i+3}$ are very small (from .10 pf to 1.0 pf) they could easily be swamped by the capacitance between the conductors being measured and the environment.

Precaution should therefore be taken to eliminate the capacitance due to the environment. One way to accomplish this is to measure the capacitance of a long

cable, and then, without disturbing the environment, cut off 1 foot of the cable and measure the capacitance of the remainder. The difference of these two values is the capacitance/ft.

(5) Although the theoretical values of the coefficients of capacitance are in good agreement with experimental data, it shoud be used only as a check on the experimental data. In practical design only the experimental values of C_{ij} should be used. This is because, in deriving Equations (21) to (28) many assumptions are made, and as mentioned in Section C, the present theory can not be applied to shielded cable, stacked cables, or cable mounted to a grounded metal. Furthermore, the types of cable are limited, and a compilation of accurate experimental data is not difficult to obtain.

III. COEFFICIENTS OF INDUCTANCE

If no magnetic materials are present in the vicinity of the rectangular conductors, the self inductance L and mutual inductance M are given by the following equations (NASA TMX-53975):

$$L\,(A,B,C) = .002A\left[\ln\frac{2A}{B+C} + \frac{1}{2} - \ln E + \frac{.2235\,(B+C)}{A}\right] \mu H \qquad [33]$$

$$M\,(A,R) = .002A\left[\ln\frac{2A}{R} - 1 + \frac{R}{A} - \frac{R^2}{4A^2}\right] \mu H \qquad [34]$$

Where A = length of conductor in cm

B = width of conductor in cm

C = thickness in cm

R = geometrical mean distance in cm

E = a correction term computed and tabulated by Grover (Inductance Calculations: Working Formulas and Tables)

It can be shown (Jackson; Classical Electrodynamics, page 167) that for a current distribution J(X,Y) at z=T in a medium of unit permeability adjacent to a semi-infinite slab of material having permeability μ and filling the half space, $z < 0$, the magnetic induction for $z > 0$ can be calculated by replacing the slab by an image current distribution

$$\frac{\mu - 1}{\mu + 1} J(x, y) \quad \text{on } z = -T \text{ plane} \qquad [35]$$

Therefore the self and mutual inductance of the rectangular conductors in a cable mounted to grounded metal of permeability are

$$L'(A, B, C) = L(A, B, C) + \frac{\mu - 1}{\mu + 1} M(\ell, 2T) \qquad [36]$$

and

$$M(\ell, R) = M(\ell, R) + \frac{\mu - 1}{\mu + 1} M\left(\ell, \sqrt{R^2 + 4T^2}\right) \qquad [37]$$

where the unprimed quantities, L and M, are respectively the self and mutual inductance when no magnetic material is in the vicinity.

IV. WAVE PROPAGATION ON FLAT CONDUCTOR CABLE

Formal mathematical theory of the wave propagation of current and voltage on multiple transmission lines has been developed since 1930's. These analyses are readily applicable to flat conductor cable for calculation of attenuation factor, phase angle, cross talk and other quantities of interest.

In Section A the expressions for current and voltage on multiple transmission lines are presented for references. For details the reader is referred to "Matrix Methods for Engineering" by Louis A Pipes.

In Section B, a special case of zero conductance and inductance is discussed. These assumptions are good approximation for flat conductor cable. Calculations of cross talk, attenuation constants and phase angles are presented in Sections C and D.

A. Outline of the Theory

The periodical current and voltage on a pair of balanced transmission lines are governed by the well-known differential equations

$$-\frac{\partial}{\partial x} V(x) = (R + j\omega L)\, I(x) \qquad [38]$$

and

$$-\frac{\partial}{\partial x} I(x) = (G + j\omega C)\, V(x) \qquad [39]$$

where $V(x)$ = potential difference between the two lines at x,

$I(x)$ = current at x,

R = resistance per unit length of the transmission lines

G = leakage conductance per unit length between the transmission lines

L = total inductance per unit length

C = total capacitance per unit length

ω = 2π (frequency) the preriodical current and voltage

The solutions to Equations (38) and (39) have the form

$$I(x) = Ae^{\Gamma x} + Be^{-\Gamma x} \qquad [40]$$

and

$$V(x) = Z_o\left(e^{\Gamma x} - Be^{-\Gamma x}\right) \qquad [41]$$

where

$$\Gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \qquad [42]$$

$$\equiv \alpha + j\beta$$

α = attenuation constant,

β = phase angle,

Z_o = characteristic impedance

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad [43]$$

and A and B are constants determined by boundary conditions.

Equations (38) and (39) can be easily generalized to describe wave propagation on multiple transmission lines:

$$-\frac{\partial V_\ell}{\partial x} = (R_\ell + j\omega L_{\ell\ell}) I_\ell(x) + \sum_{k \neq \ell} j\omega L_{\ell k} I_k(x) \qquad \text{for } \ell = 1, 2 \ldots n \qquad [44]$$

and

$$-\frac{\partial I_\ell}{\partial x} = j\omega C_{\ell\ell} V_\ell(x) + \sum_{k \neq \ell} (G_{k\ell} + j\omega C_{\ell k}) V_k(x) \qquad [45]$$

$$\text{for } \ell = 1, 2 \ldots\ldots n$$

Expressed in Matrix notation, these two equations become

$$-\frac{\partial}{\partial x} \underset{\sim}{I}(x) = \underset{\approx}{Y} \; \underset{\sim}{V}(x) \qquad [46]$$

and

$$-\frac{\partial}{\partial x} \underset{\sim}{V}(x) = \underset{\approx}{Z} \; \underset{\sim}{I}(x) \qquad [47]$$

where

$$\underset{\sim}{I}(x) = \begin{pmatrix} I_1(x) \\ I_2(x) \\ \vdots \\ I_n(x) \end{pmatrix}, \qquad \underset{\sim}{V}(x) = \begin{pmatrix} V_1(x) \\ V_2(x) \\ \vdots \\ V_n(x) \end{pmatrix} \qquad [48, 49]$$

$$\underset{\approx}{Z} = \begin{pmatrix} Z_{11} & Z_{12} & Z_{13} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & Z_{23} & \cdots & Z_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{n1} & Z_{n2} & Z_{n3} & \cdots & Z_{nn} \end{pmatrix} \qquad [50]$$

$$\underset{\approx}{Y} = \begin{pmatrix} Y_{11} & Y_{12} & Y_{13} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & Y_{23} & \cdots & Y_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Y_{n1} & Y_{n2} & Y_{n3} & \cdots & Y_{nn} \end{pmatrix} \qquad [51]$$

where

$$Z_{k\ell} = j\omega L_{k\ell} \qquad \text{for } k \neq \ell \qquad [52]$$

$$Z_{\ell\ell} = R_\ell + j\omega L_{\ell\ell} \qquad [53]$$

$$Y_{k\ell} = G_{k\ell} + j\omega C_{k\ell} \qquad \text{for } k \neq \ell \qquad [54]$$

and

$$Y_{\ell\ell} = j\omega C_{\ell\ell} \qquad [55]$$

Solutions of Equations (46) and (47) are given by Louis Pipes (Matrix Methods of Engineering):

$$\underset{\approx}{I}(x) = \sum_{r=1}^{n} \frac{\cosh(x\sqrt{m_r})}{D'(m_r)} \underset{\approx}{F}(m_r) \underset{\sim}{I}_g \; - \; \sum_{r=1}^{n} \frac{\sinh(x\sqrt{m_r})}{(\sqrt{m_r})\, D'(m_r)} \underset{\approx}{F}(m_r) \underset{\approx}{Y} \underset{\sim}{V}_g \qquad [56]$$

and

$$\underset{\sim}{V}(x) = \sum_{r=1}^{n} \frac{\cosh(x\sqrt{m_r})}{D'(m_r)} \underset{\approx}{G}(m_r) \underset{\sim}{V}_g \; - \; \sum_{r=1}^{n} \frac{\sinh(x\sqrt{m_r})}{(\sqrt{m_r})\, D'(m_r)} \underset{\approx}{F}(m_r) \underset{\approx}{Z} \underset{\sim}{I}_g \qquad [57]$$

where M_r is an eigenvalue of the following equation

$$\underset{\approx}{Y}\,\underset{\approx}{Z}\,\underset{\sim}{I}_r = m_r \underset{\sim}{I}_r \qquad [58]$$

$$\underset{\approx}{G}(m_r) = \mathrm{Adj}\left[m_r \underset{\approx}{U} - \underset{\approx}{Z}\,\underset{\approx}{Y}\right] \qquad [58a]$$

$$\underset{\approx}{F}(m_r) = \mathrm{Adj}\left[m_r \underset{\approx}{U} - \underset{\approx}{Y}\,\underset{\approx}{Z}\right] \qquad [59]$$

$$D'(m_r) = \prod_{\substack{k=1 \\ k \neq r}}^{n} (m_r - m_k) \qquad [60]$$

and $\underset{\sim}{I}_g$ and $\underset{\sim}{V}_g$ are the boundary values at the sending ends of the transmission lines.

Given cable length l, Equations (56) and (57) can be rewritten in a simpler form,

$$\underset{\sim}{I}_g = \underset{\approx}{A}\,\underset{\sim}{I}_r + \underset{\approx}{B}\,\underset{\sim}{V}_r \qquad [61]$$

$$\underset{\sim}{V}_g = \underset{\approx}{C}\,\underset{\sim}{I}_r + \underset{\approx}{D}\,\underset{\sim}{V}_r \qquad [62]$$

where r and g indicate, respectively, receiving and sending ends of the cable, and

$$\underset{\approx}{A} = \sum_{r=1}^{n} \frac{\cosh(\ell\sqrt{m_r})}{D'(m_r)}\,\underset{\approx}{F}(m_r) \qquad [63]$$

$$\underset{\approx}{B} = \sum_{r=1}^{n} \frac{\sinh(\ell\sqrt{m_r})}{\sqrt{m_r}\,D'(m_r)}\,\underset{\approx}{F}(m_r)\,\underset{\approx}{Y} \qquad [64]$$

$$\underset{\approx}{C} = \sum_{r=1}^{n} \frac{\cosh(\ell\sqrt{m_r})}{D'(m_r)}\,\underset{\approx}{G}(m_r) \qquad [65]$$

and $$\underset{\approx}{D} = \sum_{r=1}^{n} \frac{\sinh(\ell\sqrt{m_r})}{\sqrt{m_r}\, D'(m_r)} \underset{\approx}{G}(m_r) \underset{\approx}{Z} \cdot \qquad [66]$$

B. Special Case: Conductance and Inductance are Negligible

Since the leakage conductance is very small ($G = 10^{-11}$ mho/ft.) compared with ωC_{kl} and ωL_{kl} is small compared with the resistance of the conductor, we can set both G and ωL_{kl} equal to zero. Thus Equation (58) can be rewritten as,

$$j \underset{\approx}{Y} \underset{\approx}{Z}' \underset{\sim}{I}_r = j\, m_r' \underset{\sim}{I}_r \qquad (67)$$

or $$\underset{\approx}{Y} \underset{\approx}{Z}' \underset{\sim}{I}_r = m_r' \underset{\sim}{I}_r \qquad (68)$$

where $$j m_r' = m_r$$

$$\left[\underset{\approx}{Z}\right]_{\ell k} = \begin{cases} R & \text{for } \ell = k \\ 0 & \text{for } \ell \neq k \end{cases} \qquad [69]$$

$$\left[\underset{\approx}{Y}\right]_{\ell k} = j\left[\underset{\approx}{Y}'\right]_{\ell k} = j\omega C_{\ell k} \qquad [70]$$

Substituting Equation (69) in Equation (67) gives:

$$R \underset{\approx}{Y}' \underset{\sim}{I}_r = m_r' \underset{\sim}{I}_r \qquad [71]$$

Since $\underset{\approx}{Y}'$ is symmetric and real, the eigenvalues M_r' are imaginary.

Substituting $m_r = j m_r'$ into Equations (63) to (66) gives:

$$\underset{\approx}{A} = \sum_{r=1}^{n} \frac{\cosh(\ell\sqrt{m_r})}{D'(m_r)} \underset{\approx}{F}(m_r)$$

$$= \sum_{r=1}^{n} \frac{\cosh(\ell\sqrt{j m_r'})}{D'(j m_r')} \underset{\approx}{F}(j m_r')$$

$$= \sum_{r=1}^{n} \frac{\cosh(\ell\sqrt{j m_r'})}{D'(m_r')} \underset{\approx}{F}(m_r')$$

$$= \sum_{r=1}^{n} \frac{\cosh\left[\frac{\ell\sqrt{m_r'}}{\sqrt{2}}(1+j)\right]}{D'(m_r')} \underset{\approx}{F}(m_r')$$

$$= \sum_{r=1}^{n} \frac{\cosh\alpha\cos\alpha + j\sinh\alpha\sin\alpha}{D'(m_r')} \underset{\approx}{F}(m_r') \qquad [72]$$

Similarly,

$$\underset{\approx}{B} = \sum_{r=1}^{n} \frac{\sinh\alpha\cos\alpha + j\cosh\alpha\sin\alpha}{\sqrt{m_r'}\left[\frac{1+j}{\sqrt{2}}\right] D'(m_r')} \underset{\approx}{F}(m_r') \underset{\approx}{Y} \qquad [73]$$

$$\underset{\approx}{C} = \sum_{r=1}^{n} \frac{\cosh\alpha\cos\alpha + j\sinh\alpha\sin\alpha}{D'(m_r')} \underset{\approx}{G}(m_r') \qquad [74]$$

$$\underset{\approx}{D} = \sum_{r=1}^{n} \frac{\sinh\alpha\cos\alpha + j\cosh\alpha\sin\alpha}{\sqrt{m_r'}\left[\frac{1+j}{\sqrt{2}}\right] D'(m_r')} \underset{\approx}{G}(m_r') \underset{\approx}{Z} \qquad [75]$$

Where

$$\alpha = \frac{\ell\sqrt{m_r'}}{\sqrt{2}}$$

Assuming the terminating circuits are known, the currents and voltages at the receiving end are related by the equation

$$\underset{\sim}{V}_R = \underset{\approx}{F}\, \underset{\sim}{I}_R . \qquad [76]$$

Similarly, for the sending end, we have

$$\underset{\sim}{V}_g = \underset{\sim}{V}_o + \underset{\approx}{G}\, \underset{\sim}{I}_g . \qquad [77]$$

Substituting these two equations into Equations (61) and (62) gives:

$$\underset{\sim}{I}_g = \underset{\approx}{A}\, \underset{\sim}{I}_R + \underset{\approx}{B}\, \underset{\approx}{F}\, \underset{\sim}{I}_R$$

$$\underset{\sim}{V}_o + \underset{\approx}{G}\, \underset{\sim}{I}_g = \underset{\approx}{C}\, \underset{\sim}{I}_R + \underset{\approx}{D}\, \underset{\approx}{F}\, \underset{\sim}{I}_R$$

$$= (\underset{\approx}{C} + \underset{\approx}{D}\,\underset{\approx}{F})\, \underset{\sim}{I}_R$$

$$= (\underset{\approx}{C} + \underset{\approx}{D}\,\underset{\approx}{F})(\underset{\approx}{A} + \underset{\approx}{B}\,\underset{\approx}{F})^{-1} \underset{\sim}{I}_g$$

Thus

$$\underset{\sim}{I}_g = \left[(\underset{\approx}{C} + \underset{\approx}{D}\,\underset{\approx}{F})(\underset{\approx}{A} + \underset{\approx}{B}\,\underset{\approx}{F})^{-1} - \underset{\approx}{G} \right]^{-1} \underset{\sim}{V}_o . \qquad [78]$$

C. Crosstalk

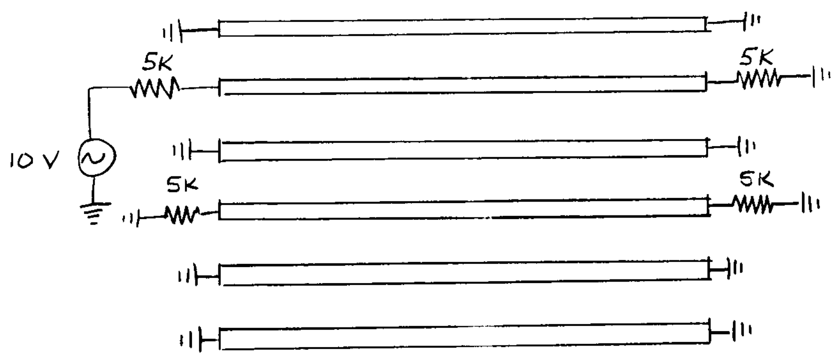
The theory developed in the preceding two sections is readily applicable to investigation of the response of flat conductor cable to various terminating circuits (sending end circuit contains signal source). In this section the voltages and currents at the receiving and sending ends are calculated for the circuit in Figure 8. For the circuit in Figure 8,

$$[\underset{\approx}{F}]_{2,2} = [\underset{\approx}{F}]_{4,4} = 5\,K\Omega \qquad [79]$$

$$[\underset{\approx}{G}]_{2,2} = [G]_{4,4} = -5\,K\Omega \qquad [80]$$

$$\left[\underset{\approx}{F} \right]_{i,\gamma} = \left[\underset{\approx}{G} \right]_{i,\gamma} = 0 \qquad [81]$$

and $$\underset{\sim}{V_o} = \begin{pmatrix} 0 \\ 10 \text{ Volts} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} . \qquad [82]$$



Combining Equations (61), (62), and (78) - (82), we can calculate the currents and voltages at both the receiving and sending ends of the cable. Of particular interest is the voltage developed across the receiving end resistance of the third conductor. This voltage will be calculated for various frequency and cable lengths. The results will be compared with the measurement by Walker.

V. APPENDICES

A. Derivation of Analytical Expressions for Coefficients of Capacitance of Conductors in a Single Cable

The general solutions in Regions I and II of the **Laplace** equations subject to the boundary conditions of Equations (14) and (15) can be expressed, respectively, by the following two Fourier Integrals:

$$V_{II}(x,y) = \int_0^\infty A(\alpha)\cos\alpha x\, e^{-\alpha y}\, d\alpha, \qquad [A-1]$$

and
$$V_I(x,y) = \int_0^\infty \left[B(\alpha)\, e^{-\alpha y} + C(\alpha)\, e^{\alpha y}\right]\cos\alpha x\, d\alpha. \qquad [A-2]$$

Invoking the continuity conditions Equations (16) and (17) at the surface of the dielectric, y = t, gives

$$A(\alpha)e^{-\alpha t} = B(\alpha)e^{-\alpha t} + C(\alpha)e^{\alpha t} \qquad [A-3]$$

and

$$A(\alpha)e^{-\alpha t} = \varepsilon\left[B(\alpha)e^{-\alpha t} - C(\alpha)\, e^{\alpha t}\right] \qquad [A-4]$$

Solving Equations (A-3) and (A-4) for $C(\alpha)$ in terms of $B(\alpha)$, we get

$$C(\alpha) = \frac{-1+\varepsilon}{1+\varepsilon}\, e^{-2\alpha t}\, B(\alpha) \qquad [A-5]$$

Therefore
$$V_I(x,y) = \int_0^\infty B(\alpha)\left[e^{-\alpha y} + \frac{-1+\varepsilon}{1+\varepsilon}\, e^{-2\alpha t}\, e^{\alpha y}\right]\cos\alpha x\, d\alpha \qquad [A-6]$$

The coefficients $B(\alpha)$ can be determined by invoking the boundary conditions at x =0 (Equation (13)), i.e.,

$$V_I(x,0) = \int_0^\infty B(\alpha)\left[1 + \frac{-1+\varepsilon}{1+\varepsilon}\, e^{-2\alpha t}\right]\cos\alpha x\, d\alpha \qquad [A-7]$$

$$= \begin{cases} V_0 & 0 \le x < w/2 \\ \dfrac{V_0}{d-w}\left(d - \dfrac{w}{2} - x\right) & w/2 \le x \le d - w/2 \\ 0 & x > d - w/2 \end{cases}$$

According the theory of Fourier Transform,

$$B(\alpha)\left[1 + \frac{\varepsilon-1}{\varepsilon+1} e^{-2\alpha t}\right] = \frac{2}{\pi}\left\{ V_0 \int_0^{W/2} \cos\alpha x \, dx + \right.$$

$$\frac{V_0}{d-W}\left(d - W/2\right) \int_{W/2}^{d-W/2} \cos\alpha x \, dx -$$

$$\left. \frac{V_0}{d-W} \int_{W/2}^{d-W/2} x \cos\alpha x \, dx \right\}$$

$$= \frac{2}{\pi}\left\{ V_0 \left.\frac{\sin\alpha x}{\alpha}\right|_0^{W/2} + \frac{V_0\left(d-W/2\right)}{d-W} \left.\frac{\sin\alpha x}{\alpha}\right|_{W/2}^{d-W/2} - \right.$$

$$\left. \frac{V_0}{d-W}\left[\frac{\cos\alpha x}{\alpha^2} + \frac{x \sin\alpha x}{\alpha}\right]_{W/2}^{d-W/2} \right\}$$

$$= \frac{2}{\pi}\left\{ V_0 \frac{\sin W/2}{\alpha} + \frac{V_0\left(d-W/2\right)}{d-W} \frac{\sin\alpha\left(d-W/2\right)}{\alpha} - \right.$$

$$\frac{V_0\left(d-W/2\right)}{d-W} \frac{\sin\alpha W/2}{\alpha} - \frac{V_0}{d-W}\left[\frac{\cos\alpha\left(d-W/2\right)}{\alpha^2} + \frac{\left(d-W/2\right)\sin\alpha\left(d-W/2\right)}{\alpha}\right] +$$

$$\left. \frac{V_0}{d-W}\left[\frac{\cos\alpha W/2}{\alpha^2} + \frac{W/2 \sin\alpha W/2}{\alpha}\right] \right\}$$

$$B(\alpha)\left[1+\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}\right] = \frac{2V_0}{\pi}\left\{ \frac{\sin W/2}{\alpha} + \frac{d-W/2}{d-W}\,\frac{\sin\alpha(d-W/2)}{\alpha} - \right.$$

$$\frac{d-W/2}{d-W}\,\frac{\sin\alpha W/2}{\alpha} - \frac{1}{d-W}\,\frac{\cos\alpha(d-W/2)}{\alpha^2} -$$

$$\frac{d-W/2}{d-W}\,\frac{\sin\alpha(d-W/2)}{\alpha} \div \frac{1}{d-W}\,\frac{\cos\alpha W/2}{\alpha^2} +$$

$$\left. \frac{W/2}{d-W}\,\frac{\sin\alpha W/2}{\alpha} \right\}$$

$$= \frac{2V_0}{\pi(d-W)}\,\frac{\cos\alpha W/2-\cos\alpha(d-W/2)}{\alpha^2}$$

Finally,

$$B(\alpha) = \frac{2V_0}{\pi(d-W)}\,\frac{\cos\alpha W/2-\cos\alpha(d-W/2)}{\alpha^2}\,\frac{1}{1+\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}} \qquad [A-8]$$

Substituting B (α) into Equation (A-6) gives (A-8)

$$V_I(X,Y) = \frac{2V_0}{\pi(d-W)}\int_0^\infty \left\{\left[\frac{\cos\alpha W/2-\cos\alpha(d-W/2)}{\alpha^2}\,\frac{1}{1+\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}}\right] \times\right.$$

$$\left.\left[e^{-\alpha Y}+\frac{\varepsilon-1}{\varepsilon+1}e^{-2\alpha t}e^{\alpha Y}\right]\cos\alpha x\right\}d\alpha. \qquad [A-9]$$

Since

$$\sigma(x) = -2\varepsilon\varepsilon_0\frac{\partial}{\partial Y}V(X,Y)\bigg|_{Y=0} \qquad [A-10]$$

We have

$$\theta(x) = -\frac{2\epsilon_0 2V_0}{\pi(d-w)} \int_0^{\infty} \frac{\cos\alpha w/2 - \cos\alpha(d-w/2)}{\alpha} \times$$

$$\frac{\frac{\epsilon-1}{\epsilon+1} e^{-2\alpha t} - 1}{\frac{\epsilon-1}{\epsilon+1} e^{-2\alpha t} + 1} \cos\alpha x \, d\alpha \qquad [A-11]$$

Carrying out the integration of $\theta(x)$ over the intervals, $[-w/2, w/2]$, $[d-w/2, d+w/2]$, $[2d-w/2, 2d+w/2]$, and $[3d-w/2, 3d+w/2]$ gives, respectively, $Q_0\ (C_{\gamma\gamma})$, $Q_1\ (C_{\gamma,\gamma+1})$, $Q_2\ (C_{\gamma,\gamma+2})$, and $Q_3\ (C_{\gamma,\gamma+3})$ (Equations (21) to (24)).

B. Proof that a Capacitance Bridge Measures Coefficients of Capacitance When All Conductors Other Than the Pair Being Measured are Grounded.

Assume the i^{th} conductor of a cable is connected to a sinusoidal, voltage and all other lines are grounded. The voltages can be represented by a column matrix

$$\underset{\sim}{V} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ E_0 \\ \vdots \\ 0 \\ 0 \end{pmatrix} e^{j\omega t} \qquad [A-12]$$

Substituting Equations (A-12) into Equation (9) in Section A,

$$\underset{\sim}{Q} = \underset{\approx}{C} \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ E_0 \\ \vdots \\ 0 \\ 0 \end{pmatrix} e^{j\omega t}$$

or

$$\underset{\sim}{Q} = \begin{pmatrix} C_{i,1} \\ C_{i,2} \\ \\ \\ C_{i,n} \end{pmatrix} E_o e^{j\omega t} \qquad [A-13]$$

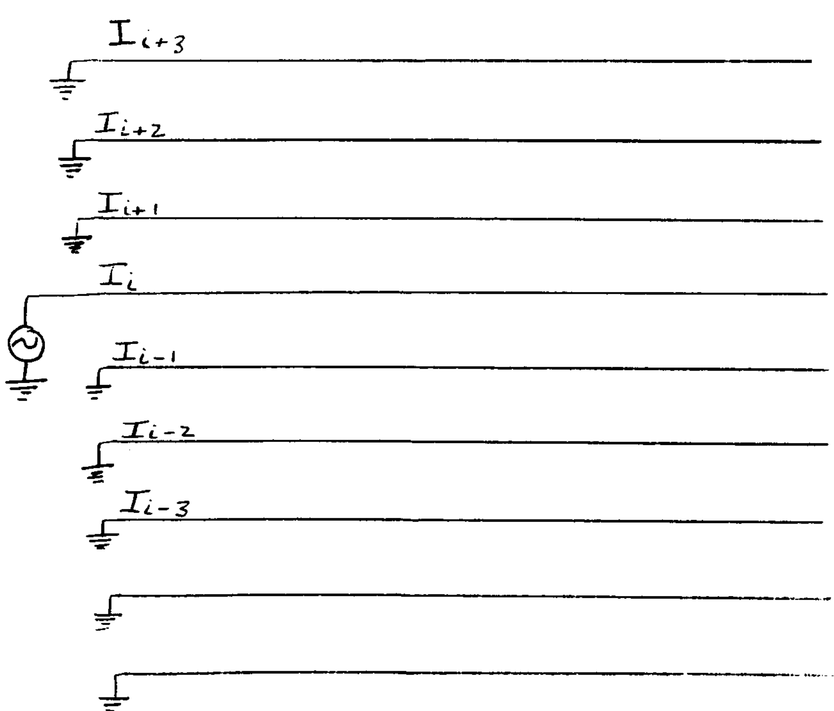
The derivative of the above equation gives

$$\underset{\sim}{I} = j\omega E_o e^{j\omega t} \begin{pmatrix} C_{i,1} \\ C_{i,2} \\ \vdots \\ C_{i,n} \end{pmatrix} \qquad [A-14]$$

or

$$I_p = j\omega C_{ip} E_o e^{j\omega t} \qquad [A-15]$$

where I_p is the current from ground to the p^{th} lines. (Figure 9)



Now the j^{th} and $(j + 1)^{th}$ lines are connected to a capacitance bridge with all remaining lines grounded as shown in Figure 11. When the bridge is balanced,

$$E' = E'' \qquad [A-16]$$

and

$$E = j\omega C\, I_{n+1}\, e^{j\omega t} \qquad [A-17]$$

Since the voltage developed across a secondary coil is proportional to the number of turns (N or N') in the coil,

$$\frac{E}{E'} = \frac{N}{N'}\,. \qquad [A-18]$$

Combining Equations (A-16 - (A-18) gives

$$\frac{N}{N'} = \frac{E}{E'} = \frac{E}{E''} = \frac{\frac{I_{n+1}}{j\omega C}}{E''}\,. \qquad [A-19]$$

From Equation (15) we have

$$\frac{N}{N'} = \frac{j\omega C_{i,i+1}\, E_0\, e^{j\omega t}}{j\frac{\omega C}{E''}}\,. \qquad [A-20]$$

Since $E'' = E_0\, e^{j\omega t}$,

$$\frac{N}{N'} = \frac{C_{i,i+1}}{C}\,. \qquad [A-21]$$

Therefore we measure the coefficient of capacitance, not the total capacitance.

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ANALYTICAL PREDICTION OF DIGITAL SIGNAL CROSSTALK OF FCC

By Dr. A. P. Belle Isle
General Electric

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SUMMARY

This paper is the result of a study effort whose aim was the development of accurate means of analyzing and predicting signal cross-talk in multi-wire digital data cables. A complete analytical model is developed for n + 1 wire systems of uniform transmission lines with arbitrary linear boundary conditions. In addition, a minimum set of parameter measurements required for the application of the model are presented. Comparisons between cross-talk predicted by this model and actual measured cross-talk are shown for a six conductor ribbon cable.

KEY WORDS

Electrical Cross-talk; Transmission Lines; Self-generated Noise; Digital Data Transmission Cables

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TESTS MADE BY W.K. Fredericks

AUTHOR Dr. A.P. Belle Isle , Adv. Comp. Engr.

COMPONENT Weapon Control Computer Engineering

APPROVED M. Fuselier - Mgr., Tech. Ser.&Admin.

INTRODUCTION

1.1 Background:

One of the major production cost factors involved in the manufacture of large, modularized electronic systems, such as strategic and tactical fire control systems, is associated with the cable assemblies used for digital data transmission between and within various sub-systems. The extensive use of balanced, shielded pairs of conductors for each bit in digital interfaces results in bulky, costly cable assemblies which are highly labor-intensive production items, due to the necessity for maintaining the isolation and integrity of each shield at every connector and junction panel. In some cases, the use of such transmission lines is necessitated by severe externally generated electrical noise, and large physical distances between sub-systems. In all too many cases, however, it is due to an excessively conservative approach to the prevention of cross-talk between signal lines. This conservatism has been necessitated by the lack of accurate means of analyzing and predicting cross-talk in multi-wire digital transmission lines. The study whose results are reported herein was aimed at correcting that lack.

1.2 Summary of Results:

The mechanisms involved in cross-talk between digital data transmission lines are the same as those in wide-band directional couplers. In essence, then, the analytical prediction of such cross-talk involves the analysis of multi-port directional couplers. The literature abounds with papers on the analysis and synthesis of 4-port directional couplers, but appears to have little to offer for the case of large numbers of conductors. What few papers exist on the general problem of 2n-port couplers inevitably seem to end up presenting the development of either a chain matrix or a scattering matrix for (n+1) - wire systems of uniform transmission lines, but applying boundary conditions and detailed analyses only for the 4-port case. (An (n+1) - wire cable is a 2n-port system.)

This paper develops a complete analytical model for (n+1) - wire systems of uniform transmission lines with arbitrary boundary conditions. In addition, a minimum set of parameter measurements required for the application of the model is presented.

Section 2.1 presents the relevant assumptions and approximations. Section 2.2 presents a rather "standard" development of the chain matrix for a system of n+1 uniform conductors. This material is by no means original, but is presented for completeness. Section 2.3 develops the complete model for the case of terminations which may be represented as arbitrary connections of Norton equivalent circuits between all possible pairs of conductors at each end. Section 2.4 develops a model for the most important class of boundary conditions which can't be represented by Norton equivalent circuits.

Section 3.1 presents the requirements for a minimum set of laboratory measurements needed to apply the model. Section 3.2 presents an example of the application of the model, and Section 3.3 presents the results of comparing cross-talk predicted by the model for an approximation to a Power NAND-to-NAND interface of the type used in MK 88 with actual measured data. The high degree of predictive accuracy obtainable with the model developed in this study may be quickly verified by turning to the last four pages of this paper.

DEVELOPMENT of the MODEL

2.1 Preliminaries:

The basic goal of this study was the accurate analytical prediction of cross-talk on arbitrary multi-wire digital data transmission cables. Ideally, then, it would be desirable to perfectly predict all voltage response waveforms at both ends of such a system, in response to arbitrary excitations and terminations. Practically, such a goal is unrealistic, so some compromises and assumptions are necessary, in the interests of analytical tractability.

The first assumption to be made is that the transmission lines are uniform. In the case of most commercially available cables, this is a reasonable assumption. Even in the case of predicting cross-talk on back panel wiring, one may break the wiring up into a cascade of different sections of uniform multi-wire transmission lines.

The second assumption is that of homogeneity and isotropicity of the system transmission medium. In the case of many conductors embedded in a common dielectric material, this is a reasonable assumption if the dielectric constant is at least twice that of free space. Thus, this is an approximation which is quite reasonable for commercially available ribbon cables, "twin-ax", etc., and becomes better or worse for multiple twisted-pair cables as a function of the relative amounts of insulation versus air or "filler" present between various twisted pairs. The higher the dielectric constant of the insulation on the individual conductors, the lower the sensitivity of the analytical predictions to the amount of space between twisted pairs.

The third assumption is that of loss-lessness of the transmission lines. This seems justified for two reasons: (1) the majority of the situations to be modelled involve short lengths of cable, so that the total attentuation is negligible; (2) even when the losses are significant, they act to reduce the cross-talk voltages as well as the "desired" voltages, making the cross-talk predictions slightly conservative.

The fourth assumption is the most severe; viz., that both the transmission line and its terminations are linear with respect to signal amplitude. With the exception of the case of voltage breakdown of the dielectric, this is certainly reasonable in the case of the transmission line.

However, the input and output impedances of driver and receiver circuits are by no stretch of the imagination linear. The only justification for assuming that they are is the widely accepted practice of doing so for other analyses. In all fairness, it must be admitted that for the case of single logic level transitions, the assumption is not all that unreasonable for bipolar integrated circuits. In addition, one may always resort to the use of piecewise linear approximations.

2.2 The Chain Matrix:

Consider a system of n+1 parallel, uniformly spaced conductors, numbered 0 through n, which are embedded in a completely homogeneous, isotropic medium with permeability μ and permittivity ϵ. In all that follows, it will be assumed that the resistivity of these conductors and the conductivity of the medium are both low enough to enable the actual electromagnetic waves propagating along this system to be adequately approximated by TEM waves. Since the TEM field configuration is the same as a two-dimensional static field configuration, the dynamics of this system may be described by the following 2n-dimensional linear partial differential equation:

$$\frac{\partial}{\partial x}\begin{bmatrix} v(t,x) \\ \hline i(t,x) \end{bmatrix} = -\left[\begin{array}{c|c} 0_n & L \\ \hline C & 0_n \end{array}\right] \cdot \frac{\partial}{\partial t}\begin{bmatrix} v(t,x) \\ \hline i(t,x) \end{bmatrix} \qquad (2.1)$$

where $v(t,x)$ is the n-dimensional vector whose components are the voltages of conductors 1 through n with respect to conductor 0 as functions of time (t) and position (x), and $i(t,x)$ is the n-dimensional vector whose components are the currents in conductors 1 through n which flow from left-to-right across planes of constant x (i.e. in the positive x-direction). The matrix L is the nxn matrix of inductances per unit length of the system, and is related to C, the matrix of capacitances per unit length by the following relation:

$$[C]\cdot[L] = [L]\cdot[C] = \mu\epsilon\cdot[1_n] \qquad (2.2)$$

where 1_n is the nxn identity matrix.

The matrix C is of the following form:

$$C = \begin{bmatrix} \sum_{j=1}^{n} c_{1j} & -c_{12} & -c_{13} & \cdots & -c_{1n} \\ -c_{21} & \sum_{j=1}^{n} c_{2j} & -c_{23} & \cdots & -c_{2n} \\ -c_{31} & -c_{32} & \sum_{j=1}^{n} c_{3j} & \cdots & -c_{3n} \\ \vdots & \vdots & \vdots & & \vdots \\ -c_{n1} & -c_{n2} & -c_{n3} & \cdots & \sum_{j=1}^{n} c_{nj} \end{bmatrix}$$

where c_{ij} is the capacitance per unit length between conductor number i and conductor number j (c_{jj} is the capacitance per unit length between conductor number j and the common return conductor, numbered "zero"), and c_{ij} of course equals c_{ji}.

In all that follows, it will be assumed that the matrix C is non-singular.

In view of equation (2.2), the system may be completely characterized by its capacitance matrix, C, and by the velocity of propagation in the medium, v_o , since $v_o = 1/\sqrt{\mu\epsilon}$. Since C is symmetric, this means that such a system of n + 1 uniform lossless transmission lines may be completely characterized by n(n + 1)/2 low frequency capacitance measurements.

Assuming that the time dependences of v and i meet the Dirichlet conditions, Laplace transformation of equation (2.1) yields

$$\frac{d}{dx} \left[\begin{array}{c} V(s,x) \\ \hline I(s,x) \end{array} \right] = - \left[\begin{array}{c|c} 0_n & sL \\ \hline sC & 0_n \end{array} \right] \cdot \left[\begin{array}{c} V(s,x) \\ \hline I(s,x) \end{array} \right] \qquad (2.3)$$

where 0_n is the nxn matrix whose elements are all zero. However, any linear differential equation of the form

$$\frac{d}{dx}\,\xi(x) = M\cdot\xi(x)$$

which has a constant nxn coefficient matrix M, all of whose components are bounded, has as its solution

$$\xi(x) = \exp(xM)\cdot\xi(0)$$

where the nxn matrix denoted as exp(xM) is defined by the following power series:

$$\exp(xM) = \sum_{k=0}^{\infty} \frac{x^k}{k!} \cdot M^k$$

Thus, since exp(-xM) is the inverse of exp(xM), which must exist for all bounded x, the voltages and currents at the "input" and "output" of a section of this (n+1) - wire system may be related as follows:

$$\left[\begin{array}{c} V(s,0) \\ \hline I(s,0) \end{array}\right] = \left[\begin{array}{c|c} T_{11}(s,x) & T_{12}(s,x) \\ \hline T_{21}(s,x) & T_{22}(s,x) \end{array}\right] \cdot \left[\begin{array}{c} V(s,x) \\ \hline I(s,x) \end{array}\right] \qquad (2.4)$$

where the 2n x 2n "chain matrix" T is defined as follows:

$$\left[\begin{array}{c|c} T_{11} & T_{12} \\ \hline T_{21} & T_{22} \end{array}\right] = \sum_{k=0}^{\infty} \frac{x^k}{k!} \cdot \left[\begin{array}{c|c} 0_n & sL \\ \hline sC & 0_n \end{array}\right]^k$$

however,

$$\left[\begin{array}{c|c} 0_n & L \\ \hline C & 0_n \end{array}\right]^2 = \left[\begin{array}{c|c} LC & 0_n \\ \hline 0_n & LC \end{array}\right] = \mu\epsilon\left[1_{2n}\right]$$

so that

$$\left[\begin{array}{c|c} 0_n & L \\ \hline C & 0_n \end{array}\right]^{2k} = (\mu\epsilon)^k \cdot \left[1_{2n}\right]$$

and

$$\left[\begin{array}{c|c} 0_n & L \\ \hline C & 0_n \end{array}\right]^{2k+1} = (\mu\epsilon)^k \cdot \left[\begin{array}{c|c} 0_n & L \\ \hline C & 0_n \end{array}\right]$$

Thus, the chain matrix may be written as

$$\left[\begin{array}{c|c} T_{11} & T_{12} \\ \hline T_{21} & T_{22} \end{array}\right] = \left[1_{2n}\right] \cdot \sum_{k=0}^{\infty} \frac{\left(\frac{sx}{v_0}\right)^{2k}}{(2k)!} + \left[\begin{array}{c|c} 0_n & L \\ \hline C & 0_n \end{array}\right] \cdot v_0 \cdot \sum_{k=0}^{\infty} \frac{\left(\frac{sx}{v_0}\right)^{2k+1}}{(2k+1)!}$$

which is, of course, the power series expansion for

$$\left[\begin{array}{c|c} T_{11} & T_{12} \\ \hline T_{21} & T_{22} \end{array}\right] = \left[1_{2n}\right] \cdot \cosh\left(\frac{sx}{v_0}\right) + \left[\begin{array}{c|c} 0_n & L \\ \hline C & 0_n \end{array}\right] \cdot v_0 \cdot \sinh\left(\frac{sx}{v_0}\right)$$

Consequently, the voltages and currents at x=0 are related to those at x as follows:

$$\left[\begin{array}{c} V(s,0) \\ \hline I(s,0) \end{array}\right] = \left[\begin{array}{c|c} \cosh\left(\frac{sx}{v_0}\right) \cdot \left[1_n\right] & v_0 \cdot \sinh\left(\frac{sx}{v_0}\right) \cdot \left[L\right] \\ \hline v_0 \cdot \sinh\left(\frac{sx}{v_0}\right) \cdot \left[C\right] & \cosh\left(\frac{sx}{v_0}\right) \cdot \left[1_n\right] \end{array}\right] \cdot \left[\begin{array}{c} V(s,x) \\ \hline I(s,x) \end{array}\right] \qquad (2.5)$$

Similarly, one may write

$$\begin{bmatrix} V(s,x) \\ \hline I(s,x) \end{bmatrix} = \left[\begin{array}{c|c} S_{11}(s,x) & S_{12}(s,x) \\ \hline S_{21}(s,x) & S_{22}(s,x) \end{array}\right] \cdot \begin{bmatrix} V(s,0) \\ \hline I(s,0) \end{bmatrix}$$

where the "forward transmission matrix" S is

$$S(s,x) = T^{-1}(s,x) = T(s,-x)$$

Thus,

$$\begin{bmatrix} V(s,x) \\ \hline I(s,x) \end{bmatrix} = \left[\begin{array}{c|c} \cosh\left(\frac{sx}{v_o}\right)\cdot\left[1_n\right] & -v_o \cdot \sinh\left(\frac{sx}{v_o}\right)\cdot\left[L\right] \\ \hline -v_o\cdot\sinh\left(\frac{sx}{v_o}\right)\cdot\left[C\right] & \cosh\left(\frac{sx}{v_o}\right)\cdot\left[1_n\right] \end{array}\right] \cdot \begin{bmatrix} V(s,0) \\ \hline I(s,0) \end{bmatrix} \tag{2.6}$$

Summarizing, then, the chain matrix and its inverse are as follows:

$$T(x,s) = \left[\begin{array}{c|c} \cosh\left(\frac{sx}{v_o}\right)\cdot\left[1_n\right] & \sinh\left(\frac{sx}{v_o}\right)\cdot\left[G_o\right]^{-1} \\ \hline \sinh\left(\frac{sx}{v_o}\right)\cdot\left[G_o\right] & \cosh\left(\frac{sx}{v_o}\right)\cdot\left[1_n\right] \end{array}\right] \tag{2.7}$$

and

$$S(x,s) = \left[\begin{array}{c|c} \cosh\left(\frac{sx}{v_o}\right)\cdot\left[1_n\right] & -\sinh\left(\frac{sx}{v_o}\right)\cdot\left[G_o\right]^{-1} \\ \hline -\sinh\left(\frac{sx}{v_o}\right)\cdot\left[G_o\right] & \cosh\left(\frac{sx}{v_o}\right)\cdot\left[1_n\right] \end{array}\right] \tag{2.8}$$

where the nxn matrix G_o is the "characteristic admittance" matrix of the system, which is defined as follows:

$$\left[G_o\right] = v_o \cdot \left[C\right] = L^{-1/2} \cdot C^{1/2} \tag{2.9}$$

For the case $n=1$ (i.e. a two wire transmission line) the matrix G_0 reduces to the inverse of the characteristic impedance of the transmission line.

By using the matrices T and S, one may describe an n+1 wire system of transmission lines as a 2n port linear circuit element (albeit with an irrational transfer function). The input and output voltages and currents are related by equations (2.5) and (2.6) in the Laplace frequency domain.

2.3 "Normal" Boundary Conditions:

In this section it will be assumed that there are no short circuits between any of the conductors at either the transmitting or receiving ends of the transmission lines. The question of short circuited terminations will be addressed in the sequel.

For the case of no shorted terminations, the boundary conditions at the "transmitting" end of an (n+1) - conductor multi-wire transmission system of length λ (i.e. at $x=0$) may be modeled as a matrix of $n(n+1)/2$ Norton equivalent circuits connected between all possible pairs of conductors. A similar model may be used at the "receiving" end of the system, denoted by $x = \lambda$.

The matrix of $n(n+1)/2$ Norton equivalent admittances (in the Laplace frequency domain) at $x=0$ will be denoted as $G_T(s)$, while the corresponding matrix of admittances at $x=\lambda$ will be denoted $G_R(s)$. Obviously, both matrices are symmetric, and are bounded since no short circuits have been permitted. Each matrix is of the following form:

$$[G] = \begin{bmatrix} \sum_{j=1}^{n} g_{1_j} & -g_{12} & \cdots & -g_{1_n} \\ -g_{21} & \sum_{j=1}^{n} g_{2_j} & \cdots & -g_{2_n} \\ \vdots & \vdots & & \vdots \\ -g_{n_1} & -g_{n2} & \cdots & \sum_{j=1}^{n} g_{n_j} \end{bmatrix}$$

where g_{ij} is the complex Norton equivalent admittance of the termination between conductor i and conductor j (g_{jj} is the termination from conductor j to the common return conductor, numbered "zero"), and g_{ij} of course equals g_{ji}.

The matrix of n(n+1)/2 Norton equivalent complex current sources at the transmitting end (x = 0) will be denoted $I_T(s)$, while that at $x = \lambda$ will be denoted by $I_R(s)$. These matrices have as their entry in row "i", column "j" the current source connected between wire i and wire j, with current defined as positive <u>into</u> wire i, and <u>out of</u> wire j. (The diagonal entries are the source currents <u>into</u> the wires coming <u>out of</u> the sources hooked between each wire and the common return conductor).

Since the current in the conductors is defined as positive in the direction of increasing x, the boundary conditions may be written as follows:

$$I(s,0) = -\left[G_T(s)\right] \cdot V(s,0) + \left[I_T(s)\right] \cdot e_n \qquad (2.10)$$

and

$$I(s,\lambda) = \left[G_R(s)\right] \cdot V(s,\lambda) - \left[I_R(s)\right] \cdot e_n \qquad (2.11)$$

where e_n is the n-dimensional vector all of whose components equal unity. However, by using the chain matrix developed in the previous section, one may write the following expression for the voltages at the "receiving" end of the system:

$$V(s,\lambda) = \cosh\left(\frac{s\lambda}{v_o}\right) \cdot V(s,0) - \sinh\left(\frac{s\lambda}{v_o}\right) \cdot \left[G_o^{-1}\right] \cdot I(s,0) \qquad (2.12)$$

Thus, by substituting (2.10) into (2.12) one obtains the following set of n equations:

$$V(s,\lambda) = \left[\cosh\left(\frac{s\lambda}{v_o}\right) \cdot \left[1_n\right] + \sinh\left(\frac{s\lambda}{v_o}\right) \cdot \left[G_o^{-1}\right] \cdot \left[G_T(s)\right]\right] \cdot V(s,0) +$$

$$-\sinh\left(\frac{s\lambda}{v_o}\right) \cdot \left[G_o^{-1}\right] \cdot \left[I_T(s)\right] \cdot e_n \qquad (2.13)$$

Similarly, since

$$V(s,0) = \cosh\left(\frac{s\lambda}{v_o}\right)\cdot V(s,\lambda) + \sinh\left(\frac{s\lambda}{v_o}\right)\cdot\left[G_o^{-1}\right]\cdot I(s,\lambda)$$

one may utilize (2.11) to write

$$V(s,0) = \left[\cosh\left(\frac{s\lambda}{v_o}\right)\cdot\left[1_n\right] + \sinh\left(\frac{s\lambda}{v_o}\right)\cdot\left[G_o^{-1}\right]\cdot\left[G_R(s)\right]\right]\cdot V(s,\lambda) +$$

$$-\sinh\left(\frac{s\lambda}{v_o}\right)\cdot\left[G_o^{-1}\right]\cdot\left[I_R(s)\right]\cdot e_n \qquad (2.14)$$

Consequently, by substituting (2.14) into (2.13) one obtains the following expression for the "receiving" end voltages as a function of the termination current sources:

$$V(s,\lambda) = \left[H(s,\lambda)\right]\cdot\left\{\left(\cosh\left(\frac{s\lambda}{v_o}\right)\cdot\left[1_n\right] + \sinh\left(\frac{s\lambda}{v_o}\right)\cdot\left[G_T(s)\right]\cdot\left[G_o^{-1}\right]\right)\cdot\right.$$

$$\left.\left[I_R(s)\right]\cdot e_n + \left[I_T(s)\right]\cdot e_n\right\} \qquad (2.15)$$

$$\left[H(s,\lambda)\right] = \left[\sinh\left(\frac{s\lambda}{v_o}\right)\cdot\left[G_o + G_T(s)\cdot G_o^{-1}\cdot G_R(s)\right] + \cosh\left(\frac{s\lambda}{v_o}\right)\cdot\right.$$

$$\left.\cdot\left[G_T(s) + G_R(s)\right]\right]^{-1} \qquad (2.16)$$

By substituting the exponential equivalents for the hyperbolic functions in (2.16) one may express this "transfer matrix" $H(s,\lambda)$ as follows:

$$\left[H(s,\lambda)\right] = 2\cdot\left[\left[B(s) + A(s)\right]\cdot e^{\frac{s\lambda}{v_o}} + \left[B(s) - A(s)\right]\cdot e^{-\frac{s\lambda}{v_o}}\right]^{-1}$$

$$(2.17)$$

where the matrices A and B are defined as

$$\left[A(s)\right] = \left[G_o\right] + \left[G_T(s)\right]\cdot\left[G_o^{-1}\right]\cdot\left[G_R(s)\right] \qquad (2.18)$$

and

$$\left[B(s)\right]=\left[G_T(s)\right]+\left[G_R(s)\right] \tag{2.19}$$

Thus, the transfer matrix can be expressed as follows (assuming $[A + B]$ is non-singular):

$$\left[H(s,\lambda)\right] = 2 \cdot \left[\left[1_n\right] - \left[A+B\right]^{-1} \cdot \left[A-B\right] \cdot e^{-2\theta}\right]^{-1} \cdot \left[A+B\right]^{-1} \cdot e^{-\theta} \tag{2.20}$$

where $\theta = s\lambda/v_o$ and the frequency dependencies of the matrices A and B have been suppressed for notational ease. However,

$$\left[1_n - Q\right]^{-1} = \sum_{k=0}^{N-1} Q^k + Q^N \cdot \left[1_n - Q\right]^{-1}$$

for any matrix Q with non-unity eigenvalues, and for any finite N. Thus, the transfer matrix $H(s,\lambda)$ may be written as follows:

$$\left[H(s,\lambda)\right] = 2 \sum_{k=0}^{N-1} \left[\left[A+B\right]^{-1} \cdot \left[A-B\right]\right]^k \cdot \left[A+B\right]^{-1} \cdot e^{-(2k+1)\theta} \tag{2.21}$$

for all finite N and all values of s other than those which satisfy

$$\det\left[\left[G_T(s)\right]+\left[G_R(s)\right]+ \tanh\left(\frac{s\lambda}{v_o}\right) \cdot \left[G_T(s) \cdot G_o^{-1} \cdot G_R(s) + G_o\right]\right] = 0 \tag{2.22}$$

which are, of course, the eigenvalues, or "poles" of the composite system. (Like all infinite-dimensional systems, this one has an infinite number of eigenvalues, resulting in this case from the presence of the hyperbolic function representing the transmission delay.)

Since $e^{-\frac{s\lambda}{v_o}}$ is the Laplace transform of a distortionless delay element with delay equal to λ/v_o, equation (2.21) shows that the response of the system to the "driving" functions produced by the Norton equivalent current sources consists of a series of reflected

waves bouncing back and forth over the n lines, with each subsequent passage down the system and back again resulting in the waves' being delayed by $2\lambda/v_o$ and "distorted" by the frequency response of the lines and their terminating admittances.

Similarly, by substituting (2.13) into (2.14) and taking advantage of the symmetry of the admittance matrices, one may obtain the following expression for the "transmitting" end voltages as a function of the termination current sources:

$$V(s,0) = \left[H'(s,\lambda)\right]\cdot\left\{\left(\cosh\left(\frac{s\lambda}{v_o}\right)\cdot\left[1_n\right] + \sinh\left(\frac{s\lambda}{v_o}\right)\cdot\left[G_R(s)\right]\cdot\left[G_o^{-1}\right]\right)\cdot\left[I_T\right]\cdot e_n + \left[I_R\right]\cdot e_n\right\} \tag{2.23}$$

where $H'(s,\lambda)$ denotes the transpose of the matrix $H(s,\lambda)$.

Thus, the total solution for all of the voltages at both ends of the line becomes

$$\left[\begin{array}{c} V(s,\lambda) \\ \hline V(s,0) \end{array}\right] = \left[\begin{array}{c|c} H(s,\lambda) & 0_n \\ \hline 0_n & H'(s,\lambda) \end{array}\right]\cdot\left[\begin{array}{c|c} T(s,\lambda) & 1_n \\ \hline 1_n & R(s,\lambda) \end{array}\right]\cdot\left[\begin{array}{c} I_R(s)\cdot e_n \\ \hline I_T(s)\cdot e_n \end{array}\right] \tag{2.24}$$

where

$$T(s,\lambda) = \frac{1}{2}\left[\left[1_n + G_T(s)\cdot G_o^{-1}\right]\cdot e^{\frac{s\lambda}{v_o}} + \left[1_n - G_T(s)\cdot G_o^{-1}\right]\cdot e^{\frac{-s\lambda}{v_o}}\right] \tag{2.25}$$

and

$$R(s,\lambda) = \frac{1}{2}\left[\left[1_n + G_R(s)\cdot G_o^{-1}\right]\cdot e^{\frac{s\lambda}{v_o}} + \left[1_n - G_R(s)\cdot G_o^{-1}\right]\cdot e^{\frac{-s\lambda}{v_o}}\right] \tag{2.26}$$

For the case of a single transmission line (i.e. n = 1) driven only at the "transmitting" end x = 0, and having purely resistive terminations, (2.24) yields

$$V(s,\lambda) = 2 \cdot \sum_{k=0}^{N-1} \frac{(g_o + g_T \cdot z_o \cdot g_R - g_T - g_R)^k}{(g_o + g_T \cdot z_o \cdot g_R + g_T + g_R)^{k+1}} \cdot e^{-(2k+1)\frac{s\lambda}{v_o}} \cdot I_T(s)$$

which reduces to the following well-known result:

$$V(s,\lambda) = \sum_{k=0}^{\infty} \left(\rho_T \cdot \rho_R e^{-2\frac{s\lambda}{v_o}}\right)^k \cdot (1+\rho_R) \cdot e^{\frac{-s\lambda}{v_o}} \cdot \frac{z_o}{z_T + z_o} \cdot z_T \cdot I_T(s)$$

where the reflection coefficients at the "transmitting" and "receiving" ends are

$$\rho_R = \frac{z_R - z_o}{z_R + z_o}$$

and

$$\rho_T = \frac{z_T - z_o}{z_T + z_o}$$

Summarizing, then, equation (2.24) is a complete analytical solution for the Laplace transforms of the voltages at both ends of an (n+1) - wire uniform lossless transmission line system as a function of the Laplace transforms of the Norton equivalent currents and equivalent admittances of arbitrary linear terminations. This solution is valid for any system of terminations which is describable by means of Norton equivalent circuits. Thus, the case of short circuits between any conductors at either end (including connecting "wires" to "shields", or running "dead wires") is not covered by this model. One important practical situation which is not covered by this model is the use of "ribbon" cable where alternate conductors are commoned at each end of the cable and tied to the common return, in order to act as partial shields between signal paths, so as to reduce cross-talk. Consequently, the analytical prediction of the effectiveness of such a scheme requires a variation of this model which will be developed in the next section.

2.4 Singular Boundary Conditions:

Consider an n+1 conductor multi-wire line with conductor "zero" (the common return) shorted to conductors number "one" through number "m" at both ends of the system. If the voltages and currents of conductors 1 through m are collected in the m-dimentional vectors $V_1(s,x)$ and $I_1(s,x)$, and if the voltages and currents of the remaining (n-m) conductors are denoted $V_2(s,x)$ and $I_2(s,x)$, then by conformally partitioning the chain matrix one may write

$$\left[\begin{array}{c} V_1(s,\lambda) \\ V_2(s,\lambda) \\ \hline I_1(s,\lambda) \\ I_2(s,\lambda) \end{array}\right] = \left[\begin{array}{c|c} \cosh\Theta \cdot \left[1_n\right] & -\sinh\Theta \cdot \begin{bmatrix} Z_{o11} & Z_{o12} \\ Z'_{o12} & Z_{o22} \end{bmatrix} \\ \hline -\sinh\Theta \cdot \begin{bmatrix} G_{o11} & G_{o12} \\ G'_{o12} & G_{o22} \end{bmatrix} & \cosh\Theta \cdot \left[1_n\right] \end{array}\right] \cdot \left[\begin{array}{c} V_1(s,0) \\ V_2(s,0) \\ \hline I_1(s,0) \\ I_2(s,0) \end{array}\right] \tag{2.27}$$

where G_o and Z_o are the characteristic admittance matrix of the system and its inverse, the characteristic impedance matrix of the system, and a prime denotes the transpose of a matrix.

In a manner similar to that used in the last section, the Norton equivalent circuits terminating the non-shorted conductors (numbered m+1 through n) yield the following boundary conditions:

$$I_2(s,0) = -G_T^* \cdot V_2(s,0) + I_T^* \cdot e_{n-m} \tag{2.28}$$

and

$$I_2(s,\lambda) = \overset{*}{G_R} \cdot V_2(s,\lambda) - \overset{*}{I_R} \cdot e_{n-m} \tag{2.29}$$

where the asterisk denotes the restriction of the matrix to conductors m+1 through n. However, according to the singular boundary conditions on wires 1 through m, $V_1(s,0)$ and $V_1(s,\lambda)$ are identically zero. Thus, by substituting (2.28) into (2.27) and solving for $V_2(s,\lambda)$ and $I_1(s,\lambda)$ one obtains the following equation:

$$\left[\begin{array}{c} V_2(s,\lambda) \\ \hline I_1(s,\lambda) \end{array}\right] = \left[\begin{array}{c|c} \cosh\Theta \cdot \left[1_{n-m}\right] + \sinh\Theta \cdot \left[Z_{o22}\right] \cdot \left[\overset{*}{G_T}\right] & -\sinh\Theta \cdot \left[Z'_{o12}\right] \\ \hline -\sinh\Theta \cdot \left[G_{o12}\right] & \cosh\Theta \cdot \left[1_m\right] \end{array}\right] \cdot$$

$$\cdot \left[\begin{array}{c} V_2(s,0) \\ \hline I_1(s,0) \end{array}\right] + \left[\begin{array}{c} -\sinh\Theta \left[Z_{o22}\right] \\ \hline \left[0_{m,n-m}\right] \end{array}\right] \cdot \overset{*}{I_T} \; e_{n-m} \tag{2.30}$$

Similarly, one may solve for $V_2(s,0)$ and $I_1(s,0)$ as follows:

$$\left[\begin{array}{c} V_2(s,0) \\ \hline I_1(s,0) \end{array}\right] = \left[\begin{array}{c|c} \cosh\Theta \cdot \left[1_{n-m}\right] + \sinh\Theta \cdot \left[Z_{o22}\right] \cdot \overset{*}{G_R} & \sinh\Theta \cdot \left[Z'_{o12}\right] \\ \hline \sinh\Theta \cdot \left[G_{o12}\right] & \cosh\Theta \cdot \left[1_m\right] \end{array}\right] \cdot$$

$$\cdot \left[\begin{array}{c} V_2(s,\lambda) \\ \hline I_1(s,\lambda) \end{array}\right] + \left[\begin{array}{c} -\sinh\Theta \cdot \left[Z_{o22}\right] \\ \hline \left[0_{m,n-m}\right] \end{array}\right] \cdot \overset{*}{I_R} \cdot e_{n-m} \tag{2.31}$$

Thus, by substituting (2.31) into (2.30) one obtains the following solution for the state variables at the "receiving" end of the system:

$$\left[\frac{V_2(s,\lambda)}{I_1(s,\lambda)}\right] = \left[E - Fe^{-2\theta}\right]^{-1} \cdot \left\{M \cdot \overset{*}{I}_R \cdot e_{n-m} + N \cdot \overset{*}{I}_T \cdot e_{n-m}\right\} \tag{2.32}$$

where the nxn matrices E and F, and the nx(n-m) matrices M and N are defined as follows:

$$E(s,\lambda) = \left[\frac{Z_{o_{22}} \cdot (\overset{*}{G}_T + \overset{*}{G}_R + \overset{*}{G}_T \cdot Z_{o_{22}} \cdot \overset{*}{G}_R) - Z'_{o_{12}} \cdot G_{o_{12}} + 1_{n-m}}{-G_{o_{12}} \cdot Z_{o_{22}} \cdot \overset{*}{G}_R} \middle| \cdots \right.$$

$$\left. \cdots \frac{Z_{o_{22}} \cdot \overset{*}{G}_T \cdot Z'_{o_{12}}}{1_m - G_{o_{12}} \cdot Z'_{o_{12}}}\right] \tag{2.33}$$

$$F(s,\lambda) = \left[\frac{Z_{o_{22}} \cdot (\overset{*}{G}_T + \overset{*}{G}_R - \overset{*}{G}_T \cdot Z_{o_{22}} \cdot \overset{*}{G}_R) + Z'_{o_{12}} \cdot G_{o_{12}} - 1_{n-m}}{-G_{o_{12}} \cdot Z_{o_{22}} \cdot \overset{*}{G}_R} \middle| \cdots \right.$$

$$\left. \cdots \frac{Z_{o_{22}} \cdot \overset{*}{G}_T \cdot Z'_{o_{12}}}{1_m - G_{o_{12}} \cdot Z'_{o_{12}}}\right] \tag{2.34}$$

$$M(s,\lambda) = \left[\frac{Z_{o_{22}} (1_{n-m} + \overset{*}{G}_T Z_{o_{22}}) + Z_{o_{22}} (1_{n-m} - \overset{*}{G}_T Z_{o_{22}}) e^{-2\theta}}{G_{o_{12}} \cdot Z_{o_{22}} \cdot (e^{-2\theta} - 1)}\right] \tag{2.35}$$

$$N(s,\lambda) = \left[\begin{array}{c} 2e^{-\Theta} \cdot Z_{o22} \\ \hline 0_{m,\ n-m} \end{array}\right] \qquad (2.36)$$

By using the same technique as used in section (2.3), the "receiving transfer matrix" becomes

$$\left[E - F \cdot e^{-2\Theta}\right]^{-1} = \sum_{k=0}^{N} [E^{-1} \cdot F]^{k} \cdot e^{-2k\Theta} \cdot \left[E^{-1}\right] = \left[P_R(s,\lambda)\right] \qquad (2.37)$$

for any finite N.

Similarly, by substituting (2.30) into (2.31), it's possible to obtain the following solution for the state variables at the "transmitting" end of the system:

$$\left[\begin{array}{c} V_2(s,0) \\ \hline -I_1(s,0) \end{array}\right] = \left[J - K\, e^{-2\Theta}\right]^{-1} \cdot \left\{ N \cdot \overset{*}{I}_R \cdot e_{n-m} + M \cdot \overset{*}{I}_T \cdot e_{n-m} \right\} \qquad (2.38)$$

where the nxm matrices J and K are defined as follows:

$$J(s,\lambda) = \left[\begin{array}{c} Z_{o22} \cdot (\overset{*}{G}_R + \overset{*}{G}_T + \overset{*}{G}_R \cdot Z_{o22} \cdot \overset{*}{G}_T) - Z'_{o12} \cdot G_{o12} + 1_{n-m} \\ \hline -G_{o12} \cdot Z_{o22} \cdot \overset{*}{G}_T \end{array}\right. \cdots$$

$$\cdots \left.\begin{array}{c} Z_{o22} \cdot \overset{*}{G}_R\ Z'_{o12} \\ \hline 1_m - G_{o12} \cdot Z'_{o12} \end{array}\right] \qquad (2.39)$$

and

$$K(s,\lambda) = \left[\frac{Z_{o_{22}} \cdot (G_R^* + G_T^* - G_R^* \cdot Z_{o_{22}} \cdot G_T^*) + Z'_{o_{12}} \cdot G_{o_{12}} - 1_{n-m}}{-G_{o_{12}} \cdot Z_{o_{22}} \cdot G_T^*} \right| \cdots$$

$$\cdots \left. \frac{Z_{o_{22}} \cdot G_R^* \cdot Z'_{o_{12}}}{1_m - G_{o_{12}} \cdot Z'_{o_{12}}} \right] \qquad (2.40)$$

As before, the "transmitting transfer matrix" can be written as follows for any finite N:

$$\left[J - K\, e^{-2\theta}\right]^{-1} = \sum_{k=0}^{N} [J^{-1} \cdot K]^k \cdot e^{-2k\theta} \cdot [J^{-1}] = [P_T(s,\lambda)] \qquad (2.41)$$

Thus, equations (2.32) through (2.41) yield a complete solution for the case of shorted "dead" wires, and the form of the solution is quite similar to the "normal" case analyzed in the previous section.

USING the MODEL

3.1 Measuring the Parameters:

As was brought out in section 2.2, an (n+1)-wire system of uniform, lossless transmission lines may be completely characterized by knowledge of (1) its propagation delay per unit of line length, and (2) its capacitance matrix C. The propagation delay may be simply determined by means of time-domain reflectometry. The symmetric nxn matrix C contains n(n+1)/2 independent parameters which require as many independent measurements for their characterization.

If the capacitance per unit length between conductor number "i" and conductor number "j" is denoted $C_{ij} = C_{ji}$, and if the capacitance per unit length between conductor number "j" and conductor zero (the common return) is denoted C_{jj}, then the capacitance matrix C is as follows:

$$C = \begin{bmatrix} \sum_{k=1}^{n} c_{1k} & -c_{12} & -c_{13} & \cdots & -c_{1n} \\ -c_{12} & \sum_{k=1}^{n} c_{2k} & -c_{23} & \cdots & -c_{2n} \\ -c_{13} & -c_{23} & \sum_{k=1}^{n} c_{3k} & \cdots & -c_{3n} \\ \vdots & \vdots & \vdots & & \vdots \\ -c_{1n} & -c_{2n} & -c_{3n} & \cdots & \sum_{k=1}^{n} c_{nk} \end{bmatrix}$$

The diagonal term in each row is merely the result of shunting all of the capacitances associated with that conductor. Thus, it is the capacitance per unit length that would be measured between that conductor and the "return" with all other conductors shorted to the "return" conductor.

Let M_{ij} denote the capacitance measured on a section of n-wire line x units long, with conductor "i" shorted to conductor "j", and all other conductors shorted to the "return" conductor. If x is much less than the wavelength (on the transmission line) at which the measurement is taken, then

$$\frac{1}{x} \cdot M_{ij} = \sum_{\substack{k=1 \\ k \neq j}}^{n} C_{ik} + \sum_{\substack{k=1 \\ k \neq i}}^{n} C_{jk} \tag{3.1}$$

for $i \neq j$, and

$$\frac{1}{x} \cdot M_{jj} = \sum_{k=1}^{n} C_{jk} \tag{3.2}$$

Thus, the diagonal terms in C may be found directly from (3.2), and the off-diagonal terms from the following equation:

$$-C_{ij} = \frac{M_{ij} - M_{ii} - M_{jj}}{2x} \tag{3.3}$$

for $i \neq j$.

3.2 An example:

The "transfer matrix" derived in section 2.2 may be written as follows:

$$\left[H(s,\lambda)\right] = 2 \cdot \sum_{k} \left[P(s) \cdot Q(s)\right]^{k} \cdot \left[P(s)\right] \cdot e^{-(2k+1)\frac{s\lambda}{v_o}} \tag{3.4}$$

where the nxn matrices P and Q are defined as follows:

$$\left[P(s)\right] = \left[G_o + G_R(s)\right]^{-1} \cdot \left[G_o\right] \cdot \left[G_o + G_T(s)\right]^{-1} \qquad (3.5)$$

$$\left[Q(s)\right] = \left[G_o - G_T(s)\right] \cdot \left[G_o^{-1}\right] \cdot \left[G_o - G_R(s)\right] \qquad (3.6)$$

Thus, for the case of purely conductive Norton equivalent admittances at both the "transmitting" and "receiving" ends of the line,

$$\left[H(s,\lambda)\right] = 2 \cdot \left\{ \left[P\right] \cdot e^{-\frac{s\lambda}{v_o}} + \left[P\right]\cdot\left[Q\right]\cdot\left[P\right]\cdot e^{-3\frac{s\lambda}{v_o}} + \left[P\right]\cdot\left[Q\right]\cdot\left[P\right]\cdot\left[Q\right]\cdot\left[P\right]\cdot e^{-5\frac{s\lambda}{v_o}} + \cdot\cdot\cdot\cdot\cdot \right\}$$

so that each reflection's passage "down and back" on the system results in modification of the original wave's amplitude only, and not its shape, since the only s-dependence is in the delay terms.

Thus, for the case of non-reactive terminations with sources only at the "transmitting" end of the system, the voltage waveforms at the "receiving" end are found from (2.24) to be

$$v(t,\lambda) = 2 \cdot \left\{ \left[P\right]\cdot i\left(t-\frac{\lambda}{v_o}\right) + \left[P\right]\cdot\left[Q\right]\cdot\left[P\right]\cdot i\left(t-3\frac{\lambda}{v_o}\right) + \left[P\right]\cdot\left[Q\right]\cdot\left[P\right]\cdot\left[Q\right]\cdot\left[P\right]\cdot i\left(t-5\frac{\lambda}{v_o}\right) + \cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot \right\}$$

where the n-vector $i(t)$ has as its j^{th} component the sum of all the Norton equivalent current sources feeding into conductor number j at the "transmitting" end of the system ($x = 0$).

Similarly, (2.24) yields the following expression for the voltage waveforms at the "transmitting" end of the system:

$$v(t,0) = \left[P \cdot W^{+}\right] \cdot i(t) + \left[PQPW^{+} + PW^{-}\right] \cdot i(t-2\frac{\lambda}{v_o}) + \left[PQPQPW^{+} + PQPW^{-}\right] \cdot i(t-4\frac{\lambda}{v_o}) + \cdots$$

where the nxn matrices W^{+} and W^{-} are defined as follows:

$$W^{+} = 1_n + G_R \cdot G_o^{-1}$$

and

$$W^{-} = 1_n - G_R \cdot G_o^{-1}$$

As noted previously, the characteristic admittance matrix G_o and the capacitance matrix C are related as follows:

$$\left[G_o\right] = v_o\left[C\right]$$

where v_o is the velocity of propagation on the system.

3.3 Laboratory Verification:

As a check on the accuracy of the previously developed analytical model, laboratory data was taken on a sample of six-conductor ribbon cable. The fifteen M_{ij} measurements were taken as impedance-versus-frequency plots, and a least-squares fit used to find an equivalent set of capacitances. The frequencies were well below the range at which the sample length (5'1") would begin to appear distributed, and well below the frequencies where the sample would resonate with the parasitic inductances of the "test jig". (The test set-up allowed stray inductances in the 10-to-100 nano-henry range, in order to keep stray capacitances low. However, these capacitances were also measured and subtracted from the results.)

The capacitance matrix for this type of cable was found to be as follows:

C Matrix (In PF/FT)

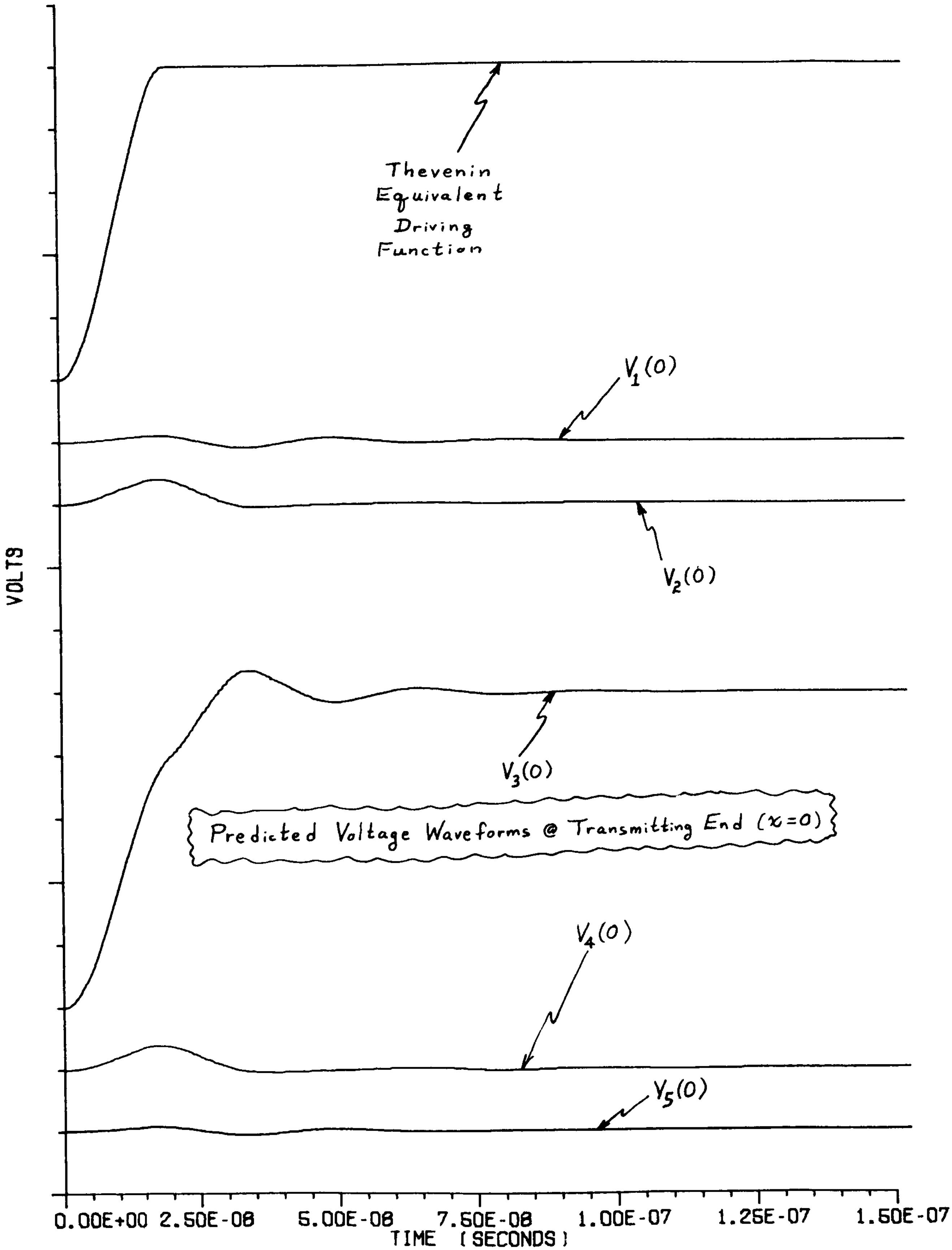
$$\begin{bmatrix} 21.80178 & -9.17657 & -0.72545 & -0.15728 & -0.47185 \\ -9.17657 & 21.60574 & -8.87225 & -0.79454 & -0.42794 \\ -0.72545 & -8.87225 & 21.42102 & -9.01494 & -1.00824 \\ -0.15728 & -0.79454 & -9.01494 & 21.83943 & -9.92077 \\ -0.47185 & -0.42794 & -1.00824 & -9.92077 & 14.39282 \end{bmatrix}$$

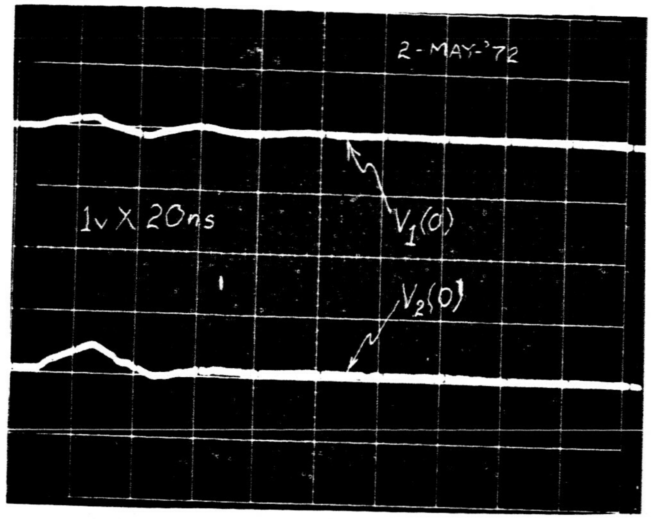
The velocity of propagation was measured with a Time Domain Reflectometer, and found to be approximately 0.6 ft./nsec. These data were plugged into the model derived in the last section, along with the following boundary conditions:

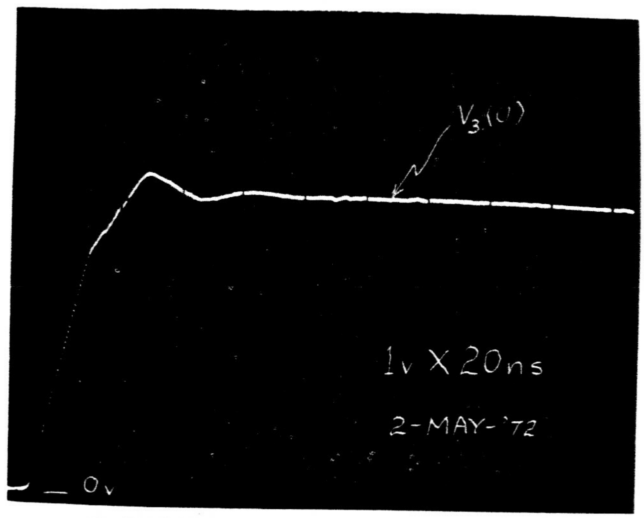
$$[G_R] = \frac{1}{4K\Omega} \cdot \left[1_5 \right] ; [G_T] = \frac{1}{25\Omega} \cdot \left[1_5 \right]$$

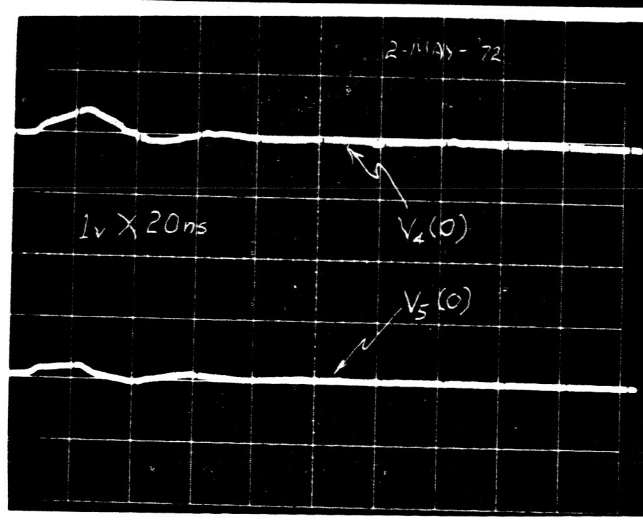
This corresponds to a linear, resistive approximation to a single-ended Power NAND-to-NAND 5-bit interface, similar to the inter-Type 2 module digital interfaces in the MK 88 Fire Control System.

A numerical approximation to this model for 5'-1" of cable was programmed on a GE-635 computer. The driving function for $i(t)$ was modelled as a cosine edge with a 20 nano-second rise time. The resulting simulation was plotted with a Cal-Comp Plotter. The predicted voltage waveforms at the "transmitting" end, $v_1(0)$ through $v_5(0)$, are shown on the next page for the case where wires 1,2,4 and 5 are held at zero volts (a logic "zero") and wire 3 is driven to five volts (a logic "one") with $i(t)$. The following page shows photographs of actual waveforms measured on this system with a Tektronix Type 564 Oscilloscope, using Type 3S76 and 3T77 sampling plug-in units and P6032 Cathode Follower Probes. The two succeeding pages show the predicted and measured waveforms at the "receiving" end, $v_1(\lambda)$ through $v_5(\lambda)$. The high degree of accuracy of prediction yielded by the analytical model is obvious.

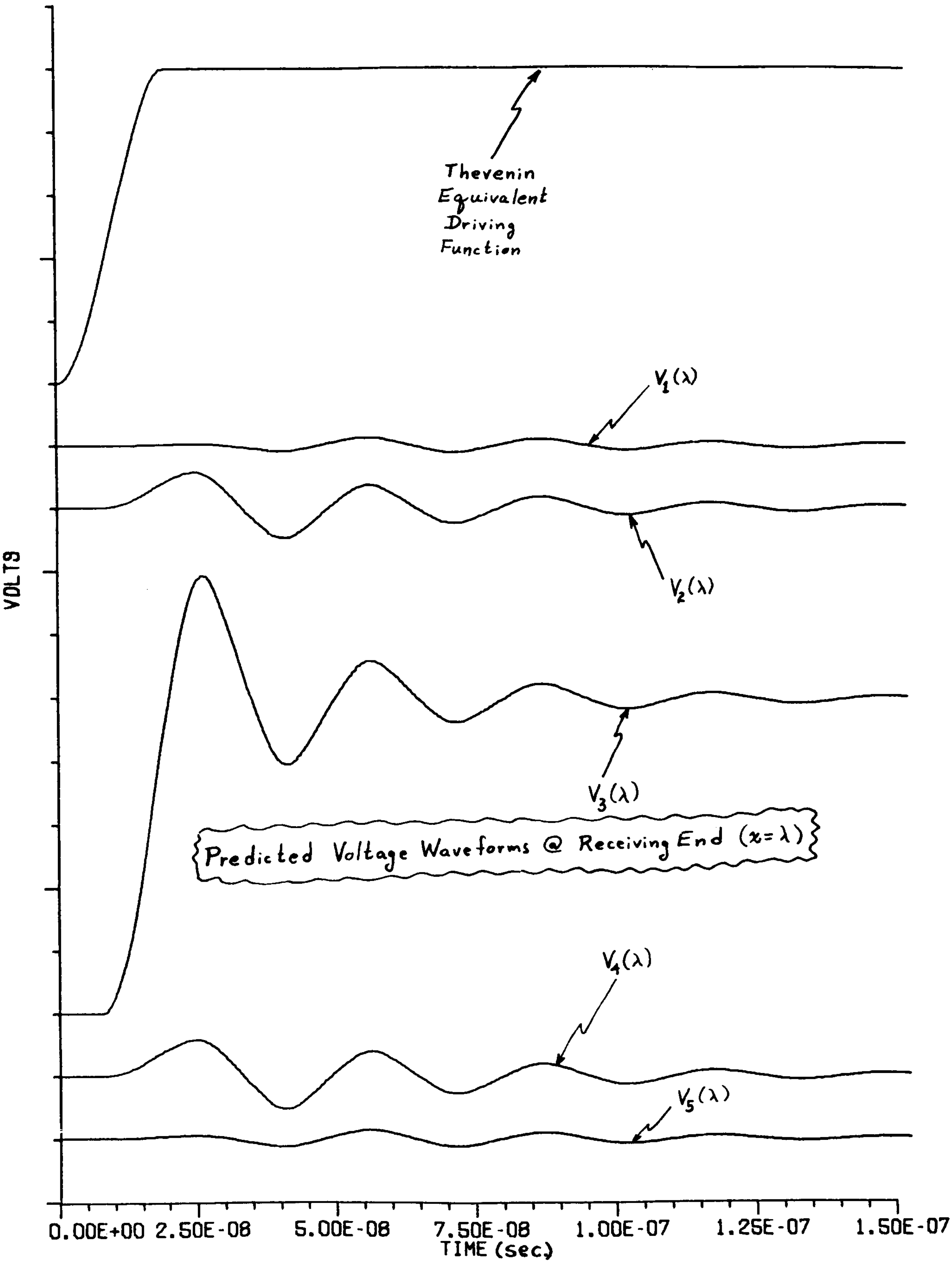

Thevenin Equivalent Driving Function
V1(0)
V2(0)
V3(0)
Predicted Voltage Waveforms @ Transmitting End (x=0)
V4(0)
V5(0)
VOLTS
0.00E+00
2.50E-08
5.00E-08
7.50E-08
1.00E-07
1.25E-07
1.50E-07
TIME (SECONDS)



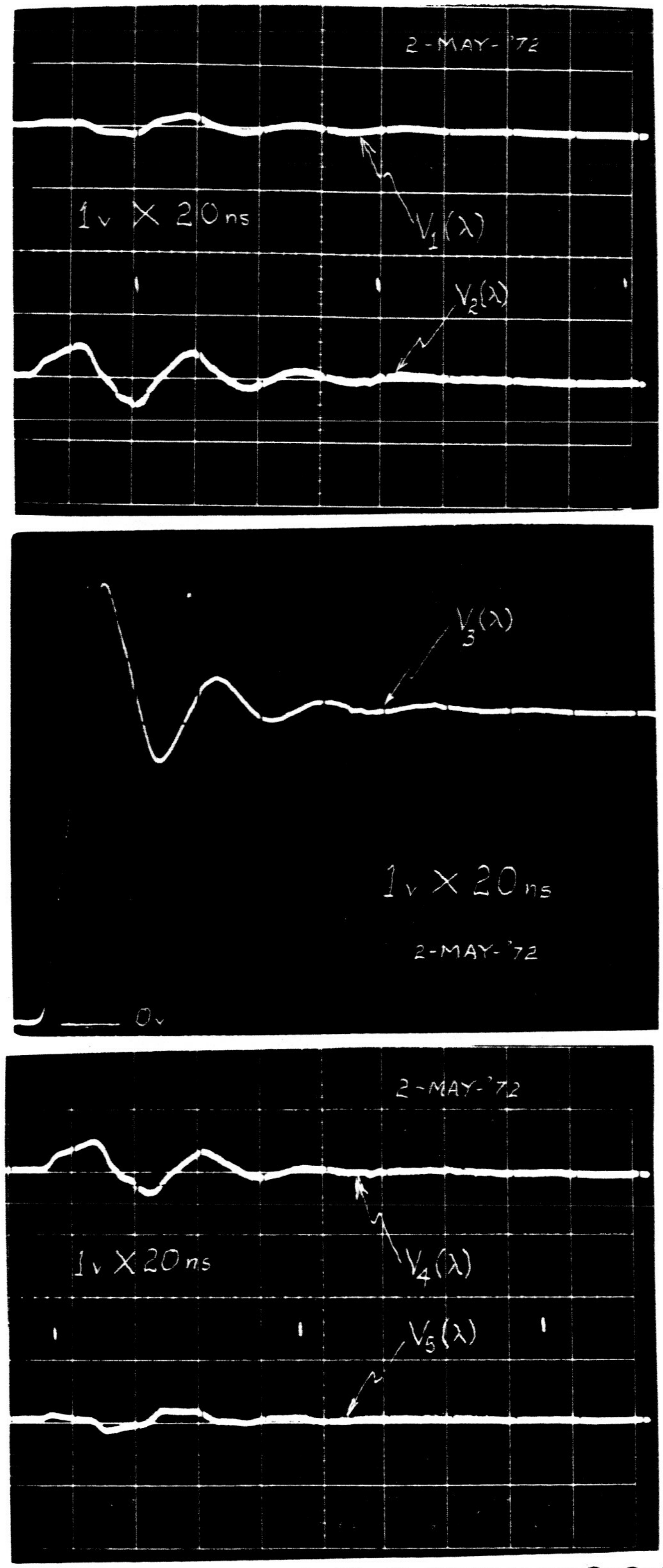




Measured Voltage Waveforms @ Transmitting End ($x=0$)



Thevenin Equivalent Driving Function
$V_1(\lambda)$
$V_2(\lambda)$
$V_3(\lambda)$
Predicted Voltage Waveforms @ Receiving End $(x=\lambda)$
$V_4(\lambda)$
$V_5(\lambda)$
VOLTS
0.00E+00
2.50E-08
5.00E-08
7.50E-08
1.00E-07
1.25E-07
1.50E-07
TIME (sec.)



Measured Voltage Waveforms @ Receiving End ($x = \lambda$)

MANUFACTURING AND QUALITY CONTROL OF FCC HARNESSES

By W. L. Malohm and J. Vandergriff
North American Rockwell

MANUFACTURING & QUALITY CONTROL OF FLAT CONDUCTOR CABLE (FCC) HARNESSES WITH DESIGN & INSTALLATION REQUIREMENTS

ABSTRACT

The Saturn V program contractors encountered many technological challenges and problems relative to inter-connecting wiring and cabling during the development stages of the Saturn program. The challenges and problems encountered during this period were not merely restricted to the design parameters, but also involved the manufacturing functions relative to fabrication, inspection, and installation. The knowledge gained from solving these problems, plus recently developed state-of-the-art techniques, materials, and processes have been documented in a report prepared for NASA/MSFC by the Space Division of North American Rockwell Corporation (SD72-SA-0060/31 July 1972). This presentation will highlight the portions of that report which deal with Flat Conductor Cable (FCC) harnesses.

INTRODUCTION

In April of 1971, NR/SD began work on the Space Vehicle and Payload Wiring Documentation Study, under the direction of NASA/MSFC. The study was primarily concerned with the evaluation and documentation of current design, fabrication, inspection, installation, and test requirements currently being utilized by the major Saturn V contractors for inter-connecting wiring and cabling of space vehicles. New state-of-the-art techniques, materials, and processes were also evaluated for inclusion in the report. In addition, the existing NASA/MSFC design and installation standards were evaluated and appropriate change recommendations made to reflect the latest design and installation criteria. The study covered the following eight types of interconnecting wire harnesses defined by NASA/MSFC:

Type I	Enclosed in fluorcarbon elastomer convolute tubing
Type II	Enclosed in TFE convolute tubing lined with fiberglass braid
Type III	Enclosed in TFE convolute tubing
Type IV	Open bundle
Type V	Combination of Type III and IV
Type VI	Enclosed in TFE heat shrink tubing
Type VII	Flexible armored harness
Type VIII	Flexible flat conductor cable harness

STUDY APPROACH

The methods used to accomplish the study effort were:

1. A survey and assessment of applicable design, quality test, and process specification and standards utilized by the major Saturn V contractors, NASA, and the military.
2. Evaluation of new materials, equipment, tools, and hardware developed by suppliers, contractors, and NASA.
3. Investigation of process techniques utilized by manufacturers (both private industry and NASA) in interconnecting wire harness development.

GENERAL

This report deals primarily with the manufacturing and quality control requirements of flat conductor cable harnesses for space vehicle and payload interconnecting systems. The secondary portion of the report deals with the derivation of supplemental documentation concerning harness design and installation requirements as required to upgrade the stature of MSFC design standard 40M39582 (Harness, Electrical Design Standard) and MSFC-SPEC-494 (Installation of Harness Assembly [Electrical Wiring], Space Vehicle, General Specification For).

FCC DESIGN AND INSTALLATION REQUIREMENTS

Many of the design and installation requirements contained in the NASA/MSFC design and installation standards are applicable to FCC harnesses. The NR study added necessary FCC requirements such as, intended use of harnesses, current carrying capacity, applicable documents, cable and connector types, folding techniques, harness securing style, routing, clamping and support criteria. The flat conductor cable and connectors added to the design and installation standards are from MIL-C-55543 and MIL-C-55544.

The addition of FCC requirements to the existing NASA/MSFC design and installation documents is a major milestone toward a greater acceptance and use of FCC.

NASA/MSFC DESIGN STANDARD REVISION

The "no-change" version of the NASA/MSFC wiring design standard 40M39582 contained requirements for harness types I through VI. The "A" revision (9/8/71) added requirements for type VII harnesses. Revisions proposed in the final report of the NR study, which includes the FCC design requirements, will be included in a subsequent revision due for release 1 February 1973. These proposed revisions are documented in NR/SD report number SD72-SA-0060.

NASA/MSFC INSTALLATION SPECIFICATION REVISION

The "no-change" version of the NASA/MSFC installation specification MSFC-SPEC-494 contains requirements for open bundle (Type IV) harnesses only. Revisions proposed in the final report of the NR study includes installation requirements for the other seven harness types, including the FCC installation requirements. These proposed revisions will be included in a subsequent revision of the NASA/MSFC specification scheduled for release 20 October 1973. The revisions are documented in NR/SD Report No. SD72-SA-0060.

MANUFACTURE AND QUALITY CONTROL OF FCC HARNESSES

Documentation of the criteria relative to manufacture and quality control of flat conductor cable harnesses was prepared on the basis of the best current and available technology, as evaluated by the NR/SD study group. A great deal of emphasis was placed on selecting only processes, methods, and techniques which are acceptable to the NASA design and installation standards. Since one of the goals was to eliminate unacceptable techniques, only those procedures and methods considered "best" were included in the document.

Some of the unique features of this volume are a manufacturing and quality flow diagram, the combining of manufacturing and quality requirements in one document, the strong use of illustrations and the coordination of this document with the design and installation documents.

The following text is the complete Volume IV from the NR study effort which details the manufacturing and quality control requirements for fabrication of FCC inter-connecting harnesses. This portion of the NR study has been released by NASA/MSFC in Technical Memorandum TMX-64685.

FOREWORD

This document is one of a series of four volumes prepared for use as a standard for manufacturing and quality control of interconnecting wire harnesses for space vehicle and payload applications.

The procedures reflected herein are based on the following four key elements:

1. Formulation of a typical manufacturing flow diagram for identification of each manufacturing and quality control process, operation, inspection and test point.
2. Identification of the various parts, materials, tools, and components, utilized in harness manufacture.
3. Acknowledgement of design standards as defined in MSFC document 40M39582, "Harness, Electrical Design Standard".
4. Acknowledgement of harness assembly installation standards defined in MSFC-SPEC-494, "General Specification for Installation of Harness Assembly (Electrical Wiring), Space Vehicle".

The complete series of documents covers the following harness types:

Volume I

Type I	Enclosed in fluorocarbon elastomer convolute tubing
Type II	Enclosed in TFE convolute tubing lined with fiberglass braid
Type III	Enclosed in TFE convolute tubing
Type V	Combination of Type III and Type IV

Volume II

Type IV	Open bundle (not enclosed)

SECTION 1
INTRODUCTION

1.1 SCOPE

The intent of this document is to establish uniform criteria to be used for acquisition, fabrication, and installation of flat-conductor cable (FCC) harnesses, used for interconnecting wiring. This document shall be used as the basis for contractors and their suppliers to establish standard manufacturing and quality control techniques.

1.2 APPLICABILITY

This document identifies and describes the manufacturing process/controls, quality control inspection criteria, and test requirements that shall be used for the following major categories:

a. Flat-Conductor Cable Preparation

b. Harness Fabrication

c. Harness Installation

1.2.1 APPLICABLE DOCUMENTS

The following documents form a part of this document to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or requests for proposals shall apply. This document shall take precedence over all other contractually imposed fabrication or inspection criteria and/or requirements relative to Type VIII - Flat-conductor cable harnesses. In case of conflict between this document and the design documents 40M39582 and MSFC-SPEC-494, the design documents will take precedence:

40M39582 - Harness, Electrical Design Standard

MSFC-SPEC-494 - Installation of Harness Assembly (Electrical Wiring), Space Vehicle, General Specification for

1.3 DEFINITIONS

For the purpose of this document, the following definitions shall apply.

1.3.1 Type VIII - Flat-conductor cable harness - shall consist of one or more flat-conductor cables; with or without breakouts; assembled with two or more electrical termination devices and so arranged that as a unit, can be assembled and handled as one assembly.

1.3.2 Flat-Conductor Cable - An electrical cable consisting of three or more solid, rectangular, nickel plated copper conductors. The conductors are embedded in high-performance insulating material in a flat and parallel configuration.

SECTION 2

MANUFACTURING FLOW DIAGRAMS

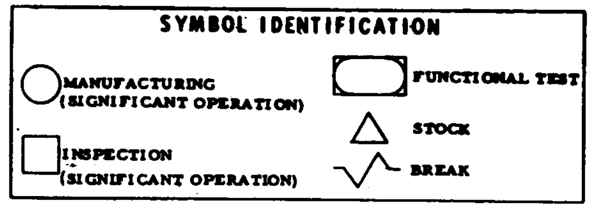
2.1 SCOPE

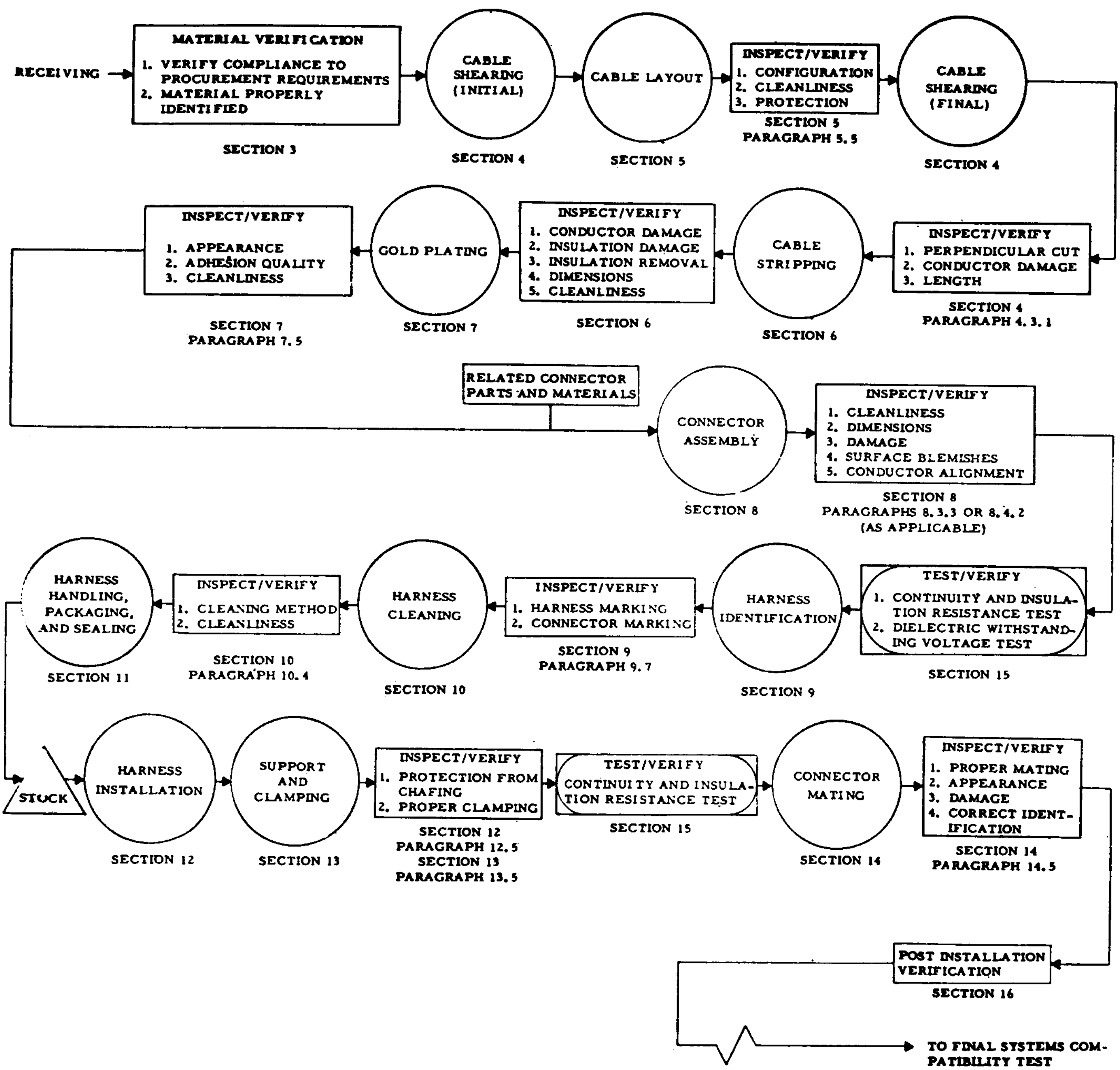
The flow diagram contained in this section depicts one of several ways in which a flat-conductor cable harness may be manufactured. Variations to the suggested flow can result from harness configuration/design changes, assembly techniques, quantity of harnesses to be fabricated, and numerous other criteria. The enclosed diagram shall be used in conjunction with the manufacturing process control and test criteria contained in this document, as a guideline for manufacture of the applicable harnesses.

2.2 APPLICABILITY

The diagram is a sequential flow chart identifying the manufacturing operations, process control points, and test requirements, that shall be used for Type VIII - flat-conductor cable, interconnecting wire harnesses.

NOTE: THIS FLOW CHART DEPICTS ONE OF SEVERAL WAYS IN WHICH A FLAT CONDUCTOR CABLE (FCC) HARNESS MAY BE MANUFACTURED. VARIATIONS TO THE FLOW CAN RESULT FROM HARNESS CONFIGURATION/DESIGN CHANGES, ASSEMBLY TECHNIQUES, AND QUANTITY OF HARNESSES TO BE FABRICATED.





FLOW CHART (TYPE VIII-FLAT CONDUCTOR CABLE HARNESS)

SECTION 3
RECEIVING INSPECTION

3.1 GENERAL

This section defines the minimum requirements for inspection verification of electrical materials acceptance, prior to issuance for manufacturing operations.

3.2 SCOPE

Electrical materials are those articles employed in fabrication and installation of interconnecting electrical cable harnesses and consist of, but are not limited to, flat conductor cable, clamps, supports, potting compounds, premolded connector plugs, connector plug components, such as seals, retaining keys, and any other parts used for assembly of premolded connectors.

3.3 PURPOSE

The purpose of acceptance inspection is to assure that suppliers of production materials have adequately performed the required inspections and tests necessary to assure a quality product which meets procurement specification requirements. Acceptance inspection tests may be conducted by 100 percent inspection or on a random sample, selected from each lot, batch, or group of materials submitted for acceptance at one time. Acceptance inspection tests shall not alleviate the supplier of his responsibility for performing all inspection and test requirements as specified in the procurement documents.

3.4 REQUIREMENTS

The materials and associated articles procured for fabrication and installation of interconnecting space vehicle electrical harnesses shall meet the following requirements and any additional requirements specified by the procurement documentation.

3.4.1 CERTIFICATION REPORTS

When specified, certification prescribed by the procurement specification shall be reviewed for conformance to requirements.

3.4.2 SAMPLING FOR ACCEPTANCE

Sampling shall be defined as a length, group, or individual units randomly selected from a lot, batch, or group submitted for acceptance inspection and test at one time. Sampling shall be planned in accordance with NHB 5300.4 (1B), paragraph 1200, which provides direction for establishing and maintaining sampling plans.

3.4.3 EXAMINATION OF MATERIALS

Each inspection lot and type of material submitted for acceptance shall be given a careful visual and dimensional examination to determine compliance with the applicable procurement specification requirements. Dimensional inspection shall be made using calibrated precision measuring instruments to determine product dimensional compliance. Materials shall be subjected to those tests as required to assure complete compliance to procurement specification acceptance and/or to validate conformance to paragraph 3.4.1. Examination of materials shall be performed in facilities as directed in paragraph 3.4.4.

3.4.4 FACILITIES

Facilities utilized for materials inspection and testing shall, as a minimum, satisfy the environmental and cleanliness levels directed by the procurement specification for the materials to be processed. Environmental and cleanliness controls shall be invoked to assure continued maintenance of prescribed levels.

3.5 RECEIVING INSPECTION AND TEST OF FLAT CONDUCTOR CABLE

Flat-conductor cable shall be subjected to visual inspection to assure compliance with the detail procurement specification requirements (i.e., identification, certification, dimensions, etc.). Samples, as defined in paragraph 3.4.2, shall be subjected to the following inspection and tests, as prescribed in the detail procurement specification.

3.5.1 IDENTIFICATION

The cable, as received, shall be identified in accordance with MIL-C-55543. Each cable roll shall be inspected for proper identification, and information shall be recorded in a receiving log for a permanent record as follows:

DATE RECEIVED	PART NUMBER LOT NUMBER	MANUFACTURE CODE	DATE OF MANUFACTURE

A sample of a convenient length, 6 or 8 inches from each lot received, should be extracted and filed with the receiving and inspection record.

3.5.2 CERTIFICATION OF CONDUCTOR MATERIAL

With each shipment of cable, certification of conductor material should be provided by the manufacturer. This information should be filed with the receiving and inspection record.

3.5.3 PACKAGING AND PACKING INSPECTION

Cables should be received in a condition in accordance with MIL-C-12000. Minimum acceptable lengths for various cable widths shall conform with the requirements outlined in MIL-C-55543.

3.5.4 CABLE DIMENSIONS

Inspection of cable dimensions on the receiving level should be divided into three inspection areas. Any variance from the dimensions specified in MIL-C-55543 should be considered a major defect and cause for rejection:

a. Cable width - The entire cable shall be checked for width dimensions and adherence to the requirements of MIL-C-55543.
b. Conductor spacing and alignment - Checking for spacing and alignment shall be accomplished to a tolerance stated in specification MIL-C-55543.
c. Conductor cross section - A sample shall be checked for conductor cross section dimensions to tolerances of specification MIL-C-55543.

3.5.5 WORKMANSHIP

The workmanship of the received cable shall be examined on a sampling or 100% basis as specified by the procurement specification. The workmanship shall reflect the use of current high grade production techniques and controls which produce a uniform and consistent product free from defects which would adversely affect the serviceability of the cable. The workmanship shall exhibit a sufficient contamination control which precludes interlaminar inclusions, conductor discoloration and moisture entrapment. The cable shall not be creased, abraded, scraped, scratched or peeled indicative of handling damage. Evidence of poor workmanship shall be cause for rejection.

3.5.6 RECEIVING INSPECTION (ELECTRICAL TEST)

The following electrical tests of cables shall be performed at receiving level:

a. Cable Electrical Continuity. Both ends of the cable length should be stripped, and a continuity check should be made on each conductor.
b. Insulation Resistance. A sample should be cut from the end of the cable roll and tested per MIL-C-55543.
c. Conductor Resistance. The dc resistance of the individual conductors should be taken on a sample basis and tested in accordance with Federal Test Method Standard No. 228, Method No. 6021.
d. Dielectric Withstanding Voltage. A sample from each inspection lot should be subjected to the dielectric withstanding voltage test per MIL-C-55543.

3.6 RECEIVING INSPECTION PREMOLDED PLUGS

Each premolded plug shall be subjected to a comprehensive visual examination for compliance with the detail procurement requirements, correct identification, and to assure that the plugs are free of contamination and/or damage. Plugs shall be packaged to provide protection against mishandling, contamination, and accelerated aging during storage.

3.6.1 IDENTIFICATION

The shipping containers of plugs as received should be identified properly in accordance with MIL-STD-129. The plugs as received should be identified

3.6.1 IDENTIFICATION (Continued)

properly in accordance with MIL-STD-130. Each shipment should be inspected for proper identification, and information should be recorded in a receiving log for a permanent record as follows:

DATE RECEIVED	PART NO. LOT NO.	MANUFACTURING CODE	DATE OF MANUFACTURE

3.6.2 MATERIAL CERTIFICATION

Certification of plug material should be provided by the manufacturer with each shipment of plugs and filed with each receiving and inspection record.

3.6.3 PACKAGING AND PACKING INSPECTION

Connector plugs should be received in a condition in accordance with MIL-P-116. Preservation and packing should be as the contract or purchase order requires. Specifics may be found in MIL-C-55544.

3.6.4 PLUG DIMENSIONS

An appropriate sampling plan should be initiated to check critical plug dimensions. All dimensions should comply with MIL-C-55544; any variance from these dimensions should be considered a major defect. The sampling plan initiated should include sectioning of the plug to inspect critical internal dimensions.

3.6.5 WORKMANSHIP

Overall quality of the plug should be checked in the following areas:

a. Flash. Flash, or excessive material on the plug, can be particularly critical if it exists in the plug window area. An appropriate sampling plan to identify this defect cannot be overstressed.

b. General Damage. The received plug should be inspected, on a sample basis, for general damage (cracks, nicks, etc.).

c. Porosity. A sample should be taken from each inspection lot and sectioned for porosity inspection. The cut section should be viewed for porosity under 3X magnification. The complete procedure for

3.6.5 **WORKMANSHIP (Continued)**

porosity identification is defined in Federal Test Method Standard No. 406, Method No. 5021.

d. Plug Material Testing. Specific parameters to ensure consistent material quality should be checked on an inspection-lot basis until a reasonable confidence level has been reached. The tests are as follows:

1. Insulation Resistance. For procedure, see Federal Test Method Standard No. 406, Method No. 4041.
2. Dielectric Withstanding Voltage. See Federal Test Method Standard No. 406, Method No. 4031.
3. Brittleness. See Federal Test Method Standard No. 406, Method No. 2051.

3.7 RECEIVING INSPECTION OF PLUG COMPONENTS

Each plug component shall be subjected to a comprehensive visual examination for compliance with detail procurement requirements, correct identification, and to assure that the components are free of contamination and/or damage. Plug components shall be packaged to provide protection from mishandling, contamination, and accelerated aging during storage.

3.7.1 BACK-SHELL/PREMOLDED PLUG CONFIGURATION

Overall quality of the back shell/premolded plug components shall be checked in the following areas:

a. Plating Consistency. A sample should be extracted from each inspection lot and checked for plating consistency. The plate should be even and free of blisters, nodules, pits, and porosity when viewed under a magnification of 3X. Finish requirements should be per MIL-C-55544.

b. Dimensions. A sample should be extracted from each inspection lot and measured for critical dimensions. Dimensional requirements are found in MIL-C-55544.

3.7.2 **PREMOLDED PLUG WEDGE AND RETAINER**

Overall quality of the premolded plug wedge and retainer components shall be checked in the following areas:

3.7.2 PREMOLDED PLUG WEDGE AND RETAINER (Continued)

a. Dimensions. Initiate a sampling plan to check critical dimensions. Dimensions are found in MIL-C-55544.

b. Material Testing. Specific parameters to ensure consistent material quality should be checked on an inspection lot basis until a reasonable confidence level has been reached. The tests are as follows:

1. Insulation Resistance. For procedure, see Federal Test Method Standard No. 406, Method No. 4041.
2. Dielectric Withstanding Voltage. See Federal Test Method Standard No. 406, Method No. 4031.
3. Brittleness. See Federal Test Method Standard No. 406, Method No. 2051.

3.7.3 SEAL

Overall quality of the seal shall be checked in the following areas:

a. Dimensions. Initiate sampling plan to check overall dimensions.

b. Hardness. Check the seal for hardness using durometer shore (a). Hardness should be Shore A78$\pm$3.

c. Age Control and Storage. The age and storage control of gasket material should be in accordance with MSFC-STD-105.

3.8 MOLDING COMPOUNDS, POTTING COMPOUNDS, AND ADHESIVES CONTROL

The general requirements for storage and in-plant control of the plating compounds and adhesives are specified herein.

3.8.1 IDENTIFICATION AND STORAGE

The identification and storage requirements are as follows:

a. Issuance of materials should be on a first-in, first-out basis.

b. Materials should be stored per manufacturer's instructions.

c. All bulk materials should be labelled and identified, and stored and handled per manufacturer's instructions. Label as follows:

Perishable Item

Batch No. (Vendor's batch or lot numbers)

Stored At (Storage temperature)

Issue Date (Date material issued from storage)

Void After (Expiration date after testing and storage)

3.8.2 STORAGE SURVEILLANCE

The storage surveillance requirements are as follows:

a. Materials which have aged beyond the void date should be impounded and retested.

b. Materials should be reidentified with a new expiration date, if tested and found acceptable.

c. Records of periodic storage surveillance should be maintained.

3.9 RECEIVING AND INSPECTION OF CLAMPS AND SUPPORTS

Cable support clamps shall be submitted to a detail physical examination to determine compliance with criteria contained in the following paragraphs.

3.9.1 IDENTIFICATION

The clamps received should be identified per MIL-STD-129. Each shipment should be inspected for proper identification and recorded in a receiving log.

3.9.2 PACKAGING AND PACKING INSPECTION

FCC clamps received should be in accordance with MIL-P-116. Preservation and packing received should conform to the contract or purchase order requirements.

3.9.3 DIMENSIONS

A sample plan should be initiated for inspecting clamp dimensions per applicable drawing.

3.9.4 WORKMANSHIP

The clamping device should be inspected for the following:

a. General damage.

b. Plating consistency (if required).

c. Spring tension (if incorporated).

d. Cushion hardness - The rubber used on the clamp should be subjected to a durometer Shore inspection to determine if the cushion hardness is within tolerance.

SECTION 4

CABLE SHEARING

4.1 GENERAL

All flat-conductor cable shall be sheared to approximate length prior to the layout process, and then sheared to exact length (including additional length needed for stripping) after completion of layout. Cable shearing equipment of either automatic or manual operation may be utilized. In addition, it is sometimes necessary to shear cable using acceptable hand cutting tools. Regardless of the method used (automatic, manual, or hand), it is essential that the cut cable meet the requirements contained in the following paragraphs.

4.2 PROCESS CONTROL REQUIREMENTS

Prior to shearing of the cable, verify correct type in accordance with applicable drawings, including size, type plating, and insulation. Make sure cable has undergone receiving inspection criteria established in Section 3 of this document, and record lot number of cable on In-Process Control Documentation. Close visual examination shall be performed on the cable, and as a minimum, the following conditions shall be inspected for:

a. Air bubbles below the insulation surface.

b. Separation of insulation material from the conductors.

c. Damaged or broken conductors.

d. General damage, such as kinks, abrasions, cracks, or dents.

4.2.1 CLEANLINESS

The work area used for shearing cable shall exhibit a clean and orderly appearance. All dirt, grease, oil, chips, and other foreign material shall be removed from tools, equipment, and work areas.

4.2.2 EQUIPMENT/TOOL REQUIREMENTS

Hand or machine shearing equipment and tools shall be periodically certified per NHB5300.4(1B). A sticker or other device shall be attached to each tool or piece of equipment indicating certification and the next recertification due date. The work produced shall be checked to assure

4.2.2 EQUIPMENT/TOOL REQUIREMENTS (Continued)

that the insulation has not been punctured, crushed, or otherwise damaged, and that the cable ends are cut square. Cutting efficiency shall be maintained by replacing blades and calibrating when necessary.

4.3 CABLE SHEARING OPERATIONS

The shearing operations shall be performed in such a manner that the conductors and insulation are not damaged adjacent to the cut end. Wire shearing equipment or tools shall not cut, extrude, or otherwise damage adjacent insulation. Repetitive occurrences of improper shearing of the cable shall be cause for maintenance and/or re-calibration of the equipment.

4.3.1 SHEARING VERIFICATION REQUIREMENTS

Cable shearing should be performed using precision shears of either the hand operated, manual, or automatic type. Regardless of the type of tool/equipment used, there are three basic requirements to be met in the shearing operation:

a. The cut must be perpendicular to the conductors.

b. The conductor ends must not be deformed.

c. The linear dimensions should be accurate.

NOTE: The cut length shall include the mockup cable length plus proper allowance for strip dimensions.

SECTION 5
CABLE LAYOUT

5.1 GENERAL

This section establishes the fabrication criteria that pertains to grouping, layout, folding, splitting, and bundling of flat-conductor cables into the desired harness configuration. Several other elements relative to harness fabrication (shearing, stripping, etc.) are covered elsewhere in this document and should be referred to where applicable.

5.2 PROCESS CONTROL REQUIREMENTS

Prior to performing cable layout operations, verify correct type cable and that shearing operation has been properly performed. Make sure the cables have not been damaged and necessary process control verification has been performed. In addition to the preceding process control requirements, the control and handling precautions described in the following paragraphs shall be applied.

5.2.1 CONTROL AND CLEANLINESS OF MOCKUP AREAS

All mockup of flat-conductor cable shall be performed in a controlled area. The general working area and benches shall be maintained in a clean and orderly condition at all times. Only tools, fixtures, equipment, etc., which are required to perform the task shall be allowed in the area. Supply cabinets or shelves used to store cable, components, hardware, etc., shall be set aside from the immediate work area, and shall be maintained in a clean and orderly condition to avoid contamination of the cable and associated materials being assembled.

5.2.2 CABLE PROTECTION

All mockup boards or fixtures shall be inspected for sharp edges, protrusions, and any other conditions that may damage the flat-conductor cable insulation. All metallic guides and supports shall be covered with protective sleeving or coating.

5.3 FABRICATION AND HANDLING PRECAUTIONS

The fabrication and handling of flat-conductor cables and cable harness assemblies requires reasonable care to prevent damage and to assure cleanliness. In addition to the handling and packaging procedures described in Section 11, the following precautions shall be observed:

a. Cables and cable assemblies shall be fully supported at all times. They shall not be allowed to hang over the edges of work surfaces or to lay on protrusions that may cause damage to conductors or insulation. In no instance will they be placed on a surface, such as a floor, where they may be stepped on or damaged by vehicular traffic. Tools or other foreign objects shall not be layed on cables during fabrication or stowage.

b. During handling, care shall be exercised to prevent cables from being dragged over any surface. They shall be fully supported and lifted when moved.

5.3.1 CLEANLINESS PRECAUTIONS

Incomplete cable harness assemblies not in work (on benches or jig boards) shall be completely covered with polyethylene film or equivalent that will not degrade the intent of the completed harness. Work areas shall be clean at all times. Only tools in use shall be allowed on the working surfaces of benches and jig boards.

5.4 LAYOUT

To facilitate installation and maintenance, cable harness configurations should be developed utilizing mockups or jig boards. When performing harness layout operations, particular attention must be paid to cable conductor registration in the plugs and cable segment registration in the harness runs. The cable identification provided by the cable manufacturer, along one edge of the flat-conductor cable, identifies the index edge for each cable segment.

5.4.1 CABLE FOLDING

Variations in harness direction or harness branch breakouts can be performed by folding the flat-conductor cable over on itself. Various cable folding techniques are used, as illustrated in Figure 1, to provide the direction changes and cable registration required. Nonshielded flat-conductor cable can be folded flat on itself with no bend radius required. In

5.4.1 CABLE FOLDING (Continued)

those areas where cables branch out of major runs, or where the major run changes its direction by folding, there are two methods to be considered, as shown in Figure 2. Folding by group provides neater bundles and additional support, with fewer exposed edges. Folding by cable makes it much easier to install, remove, and replace individual cable assemblies. It is recommended that a maximum of ten cables be folded in a bundle. If there are more than ten cables in one run, a new run should be started along side the first. Cable folding operations shall be performed with an appropriate flat-conductor cable folding tool, as illustrated in Figure 3.

5.5 PROCESS VERIFICATION REQUIREMENTS

Flat-conductor cable harness layouts shall be inspected for compatibility of the harness configuration with the applicable mockup, fixture, jigboard, and/or engineering design drawing. Check for the proper bend-angle after folding and for damage around the fold area; delamination, conductor breakage, damaged insulation, etc.

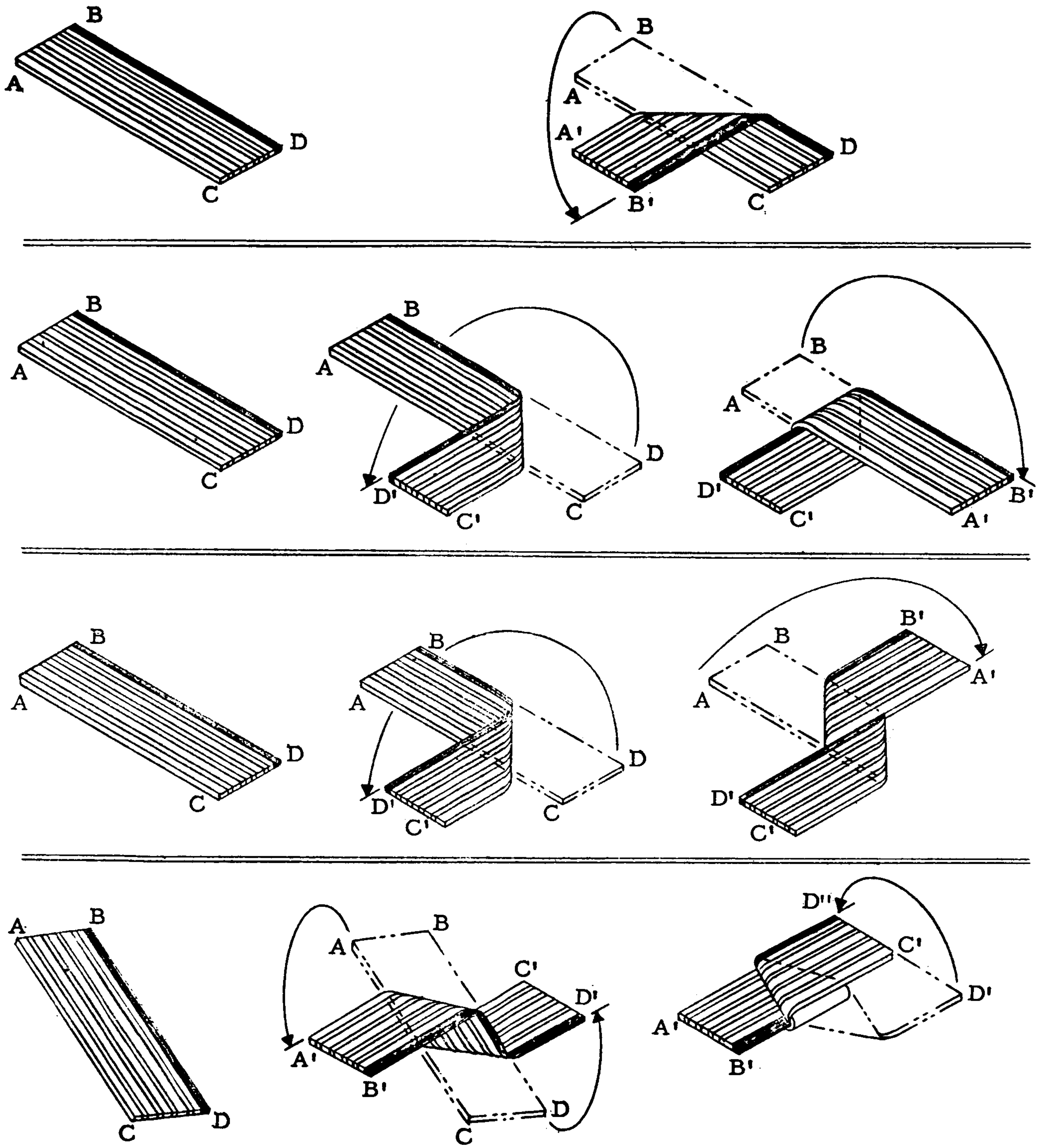
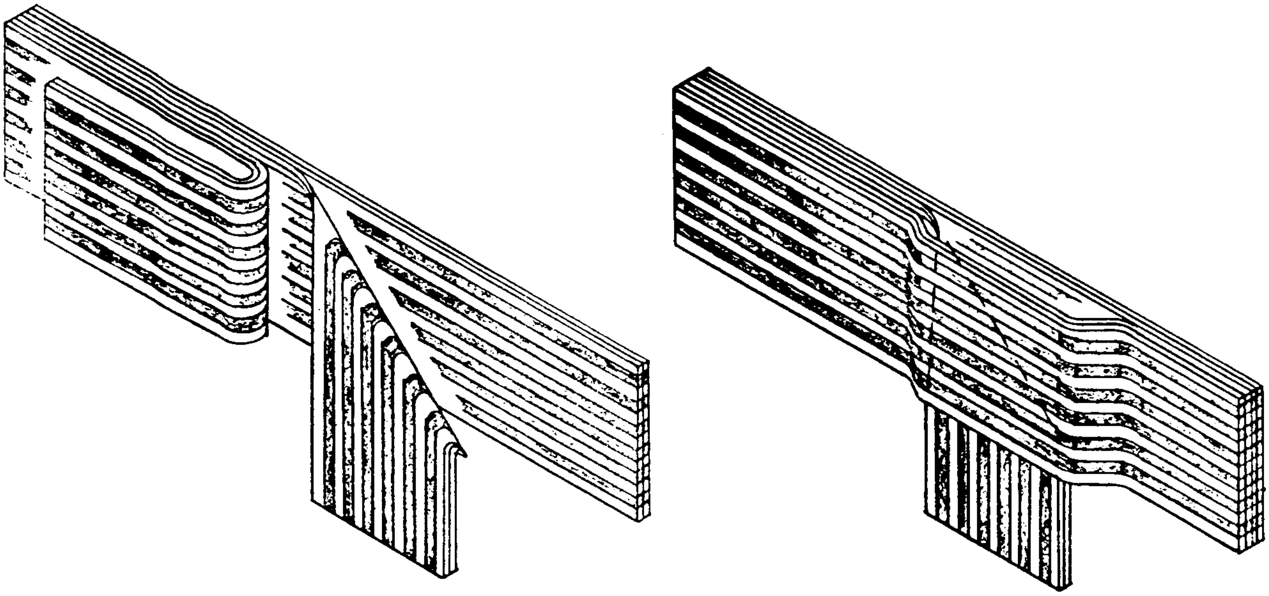
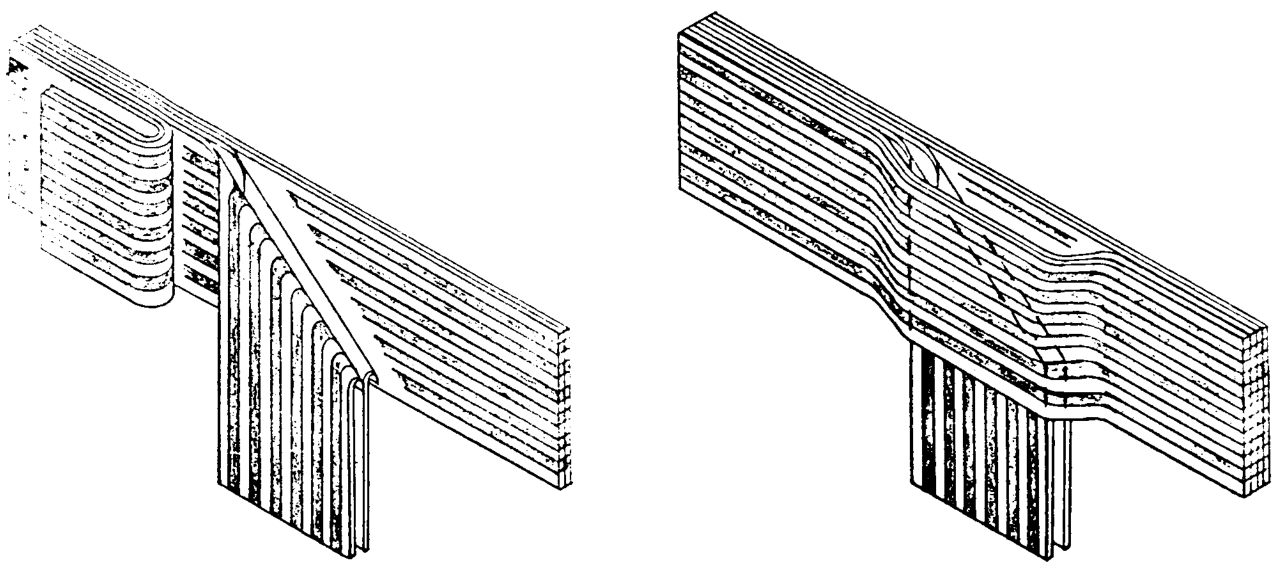


FIGURE 5-1 FCC FOLDING TECHNIQUES

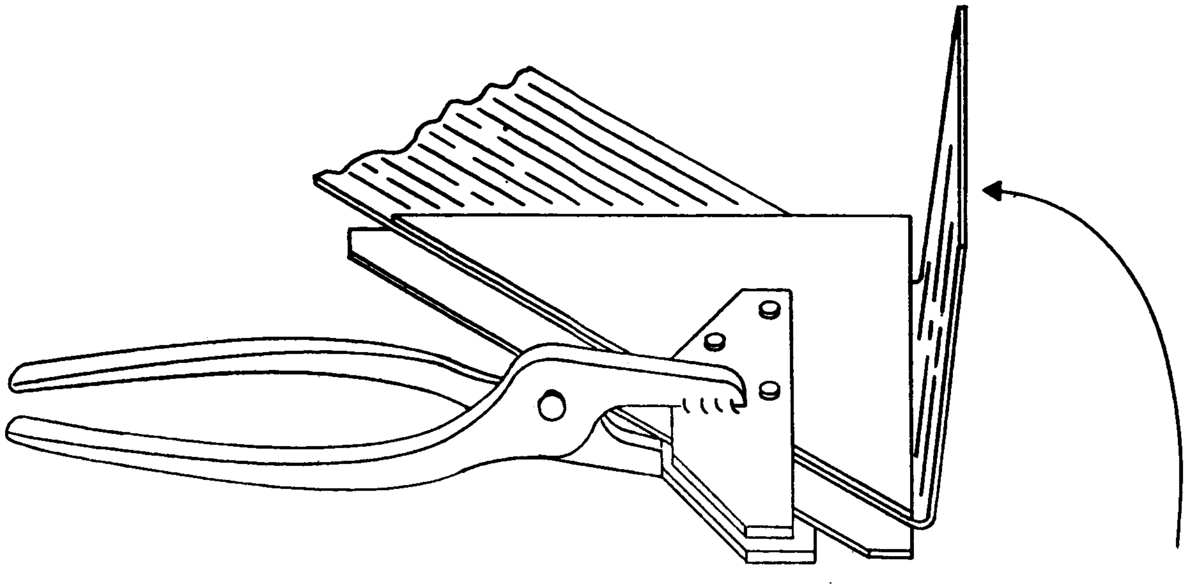


FOLDING BY GROUPS



FOLDING BY CABLE

FIGURE 5-2 FCC BRANCH BREAKOUT FOLDS



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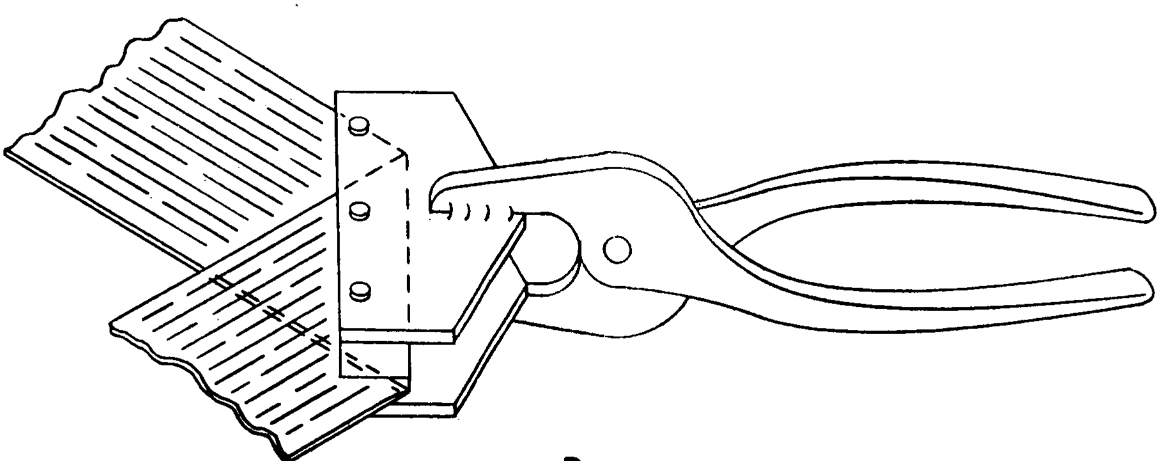


B

FIGURE 5-3 FCC FOLDING TOOLS

SECTION 6
CABLE STRIPPING

6.1 GENERAL

The intent of this section is to establish techniques for the removal of insulation from flat-conductor cable. Several methods of removing insulation have been developed, but only those methods acceptable for removal of polyimide fluorinated ethylene propylene (FEP) insulations shall be covered in this section.

6.2 PROCESS CONTROL REQUIREMENTS

Prior to stripping flat-conductor cable, verify that the cable has been cut to the required length, including proper allowance for strip dimensions, and that the cable insulation is free of nicks, cuts, or abrasions. Assure that the harness layout is in the correct configuration and the cable has been sheared perpendicular to the conductor lay.

6.2.1 GENERAL PROCESS ACCEPTANCE CRITERIA

All methods that are used in stripping cable shall be in accordance with applicable standards and specifications. The stripping operations shall be performed in such a manner that the conductors are not severed, scratched, or nicked. Minor longitudinal scratches and nicks on conductors shall be acceptable on non-plated conductors, but such scratches and nicks shall not penetrate through the plating on nickel plated conductors. The stripline should be even, and clean and free of all residual insulation or bonding agents, and no insulation should be left between the conductors.

6.2.2 OPERATOR QUALIFICATIONS

Personnel involved in insulation stripping operations shall be trained in the specific stripping process and meet the following minimum requirements:

a. Be familiar with the requirements of this document and associated documentation.

6.2.2 OPERATOR QUALIFICATIONS (Continued)

b. Receive instructions explaining the process requirements pertaining to stripping the specific insulation material.

c. Be skilled in the identification and use of tools/equipment required for stripping the cable insulation.

6.2.3 CLEANLINESS AND PROTECTION

The work area used for stripping of cable shall exhibit a clean and orderly appearance. All dirt, grease, oil, chips, and other foreign material shall be removed from the tools, equipment, and work area. After completion of the stripping process, the exposed conductors should be protected during handling by a device similar to the modified heavy duty paper clip illustrated in Figure 1.

6.3 MECHANICAL STRIPPING

Flat-conductor cable insulation material may be removed with a number of different mechanical techniques. The insulation material utilized, amount of insulation to be removed, and equipment availability must be considered when selecting the technique to be used. The preferred method for removing polyimide/fluorinated ethylene propylene (FEP) insulations is by one of the mechanical-cold blade processes. The following paragraphs describe the preferred mechanical stripping techniques, along with applicable precautions and process control criteria.

6.3.1 EQUIPMENT REQUIREMENTS

Mechanical stripping equipment shall be periodically certified per NHB 5300.4 (1B). A sticker or other method shall be attached to each piece of equipment indicating certification and the next recertification due date. The work produced shall be checked to assure that the insulation has been properly removed without conductor damage or damage to adjacent insulation. Stripping efficiency shall be maintained by replacing blades and calibrating when necessary.

6.3.2 MECHANICAL-COLD BLADE STRIPPING

Flat-conductor cables with FEP-bonded polyimide insulation can be stripped easily and quickly with a sharp blade stripper, without applying heat. The success of the cold blade stripper is dependent upon the bond of FEP conductors. The principle of this method is the use of a sharp blade that fractures the thin polyimide film and into the FEP layer, but does not contact the cable conductors. Figures 2 and 3 illustrate two types of stripping operations which may be utilized for insulation removal. Cold blade stripping shall be performed using manufacturer's instructions for the specific type equipment, in conjunction with the following procedures:

a. Verify that blade clearance gages are adjusted to cut through the cable insulation, but do not touch the conductors.
b. Position the cable in the desired position to obtain the correct strip length and clamp in place.
c. Strip the cable insulation.
d. Remove the cable and protect stripped conductors using a device similar to that illustrated in Figure 1.

6.3.3 MECHANICAL STRIPPING PROCESS VERIFICATION

Mechanical stripping process verification shall consist of the following general inspection criteria:

a. Conductor Damage - Particular attention must be given to conductor damage that may be caused by the knife blade. The conductors, under an ample magnification, should be observed for nicks, scratches, abrasions, bends, plating defects.
b. Complete insulation Removal - The stripline should be even, clean and free of all residual insulation and bonding agents. No insulation shall be left between the conductors. Each conductor should be checked under magnification for residual insulation and bonding agents. If the insulation is not properly removed, samples should be run on the particular stripping device being used to determine the appropriate stripping pressure to effectively strip the cable. The bond strength from cable to cable may vary; therefore it will be necessary at times to perform the task just described.

6.3.3 MECHANICAL STRIPPING PROCESS VERIFICATION (Continued)

c. Conductor and Insulation Cleanliness - Each conductor should be inspected for cleanliness after stripping.

d. Dimension of Strip - Each stripped cable should be measured for proper strip length.

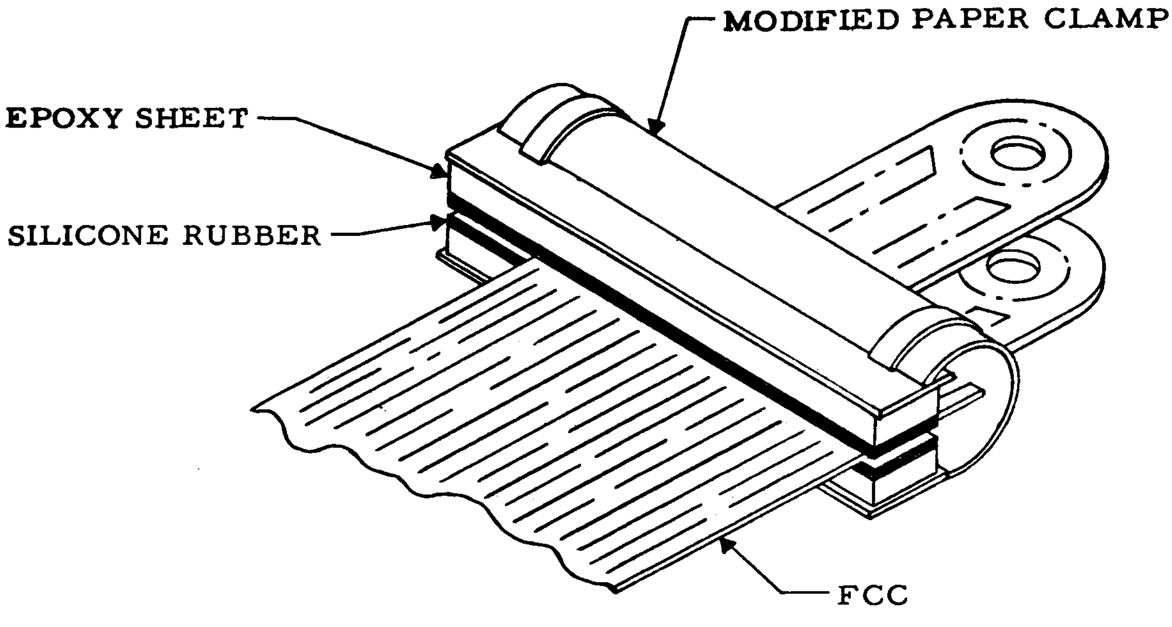


FIGURE 6-1 CONDUCTOR PROTECTING CLIP

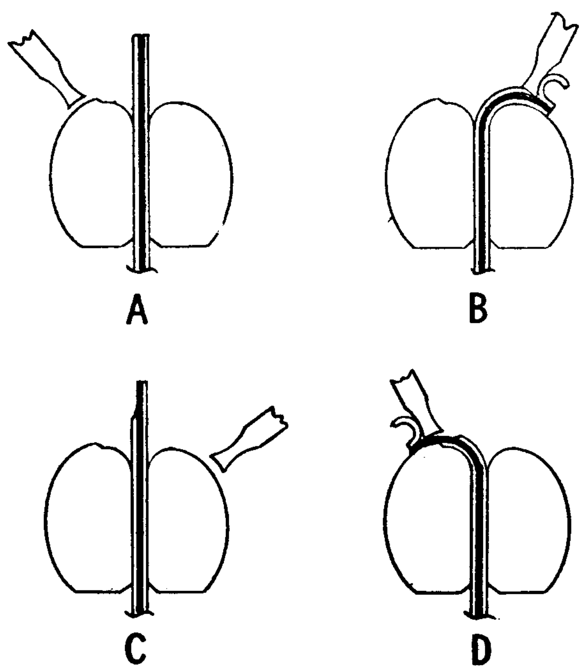


FIGURE 6-2 STRIPPING OPERATIONS-NASA MECHANICAL STRIPPER

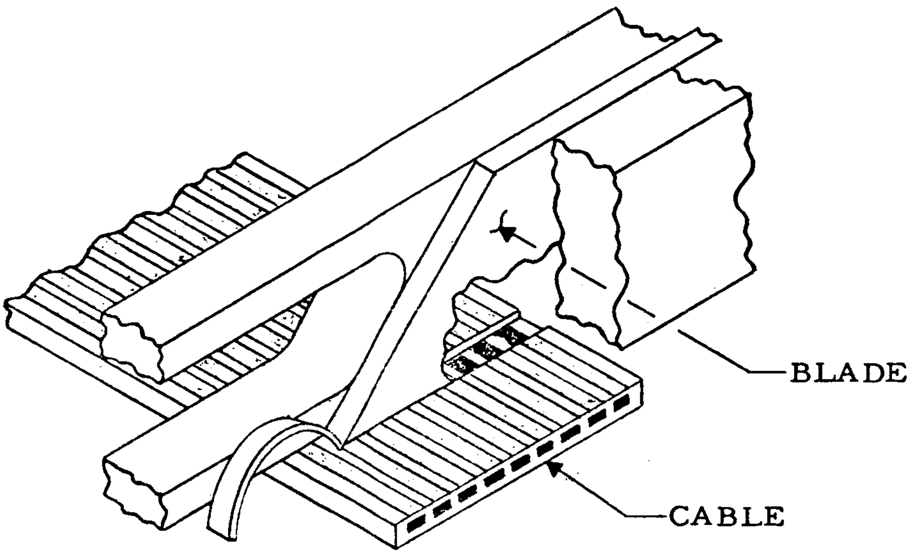


FIGURE 6-3 BLADE ACTION OF THE HOBEL STRIPPER

SECTION 7
CONDUCTOR PLATING

7.1 GENERAL

This section establishes the requirements for gold plating of flat-conductor cable conductors.

7.2 PURPOSE

The procedures contained in the following paragraphs apply to the gold plating of the nickel-plated conductors, used in the flat-conductor cable, conductor-contact plug system. The gold plating serves two purposes: (1) excellent surface conductivity, and (2) resistance to contact wear.

7.3 PROCESS CONTROL REQUIREMENTS

Prior to performing the gold plating process, examine the conductors in the area where the insulation has been removed. Remove any visible particles of insulation, adhesive or adhesive smear. Picks, tweezers, tissues and approved solvents may be used, but care must be taken to prevent damage to the nickel-plated conductors and/or cable insulation. During the cleaning and preparation processes exercise sufficient caution to prevent damage to the conductors such as cuts, nicks, scratches and excessive distortion.

7.4 GOLD PLATING

Gold plating shall be applied to the stripped, nickel-plated conductors of flat-conductor cable for improved surface conductance and corrosion resistance. Plating of the conductor contact areas with gold shall be performed as described in the following paragraphs and as sequenced in Figure 1. In addition, the gold plated surfaces shall meet the requirements established in Military Specification MIL-G-45204, Gold Plating (Electro-deposited), Type II, Class 1.

7.4.1 PREPARATION FOR GOLD PLATING

After verification that the stripped cable conductors have been properly nickel plated, the conductors shall be prepared for gold plating as described in the following procedure:

7.4.1 PREPARATION FOR GOLD PLATING (Continued)

NOTE: To minimize wicking of the plating solution, do not submerge cable into cleaning solution beyond the stripped portion of the conductors.

a. Electrically connect the FCC conductors to the plating cathode rod. Connection may be made with conductive electrical tape or spring type clamps.

   CAUTION: The connection method shall produce no damage, bending, or excessive distortion to the conductors.

b. While applying 6-volts to the cable conductors, dip the exposed conductors into the alkaline solution. Dip time shall be held to a minimum which will produce a water break free surface. Dip time shall not exceed 20 seconds.

c. Immediately upon removal from the alkaline cleaning solution, spray rinse with deionized water for 30 to 45 seconds. Examine for a water break free surface. To achieve a water break free surface, step b may be repeated but not to exceed a 20 second exposure to the alkaline solution.

d. While applying 6-volts to the cable conductors, dip the exposed conductors into a 10% (ACS) sulphuric acid solution. Dip time shall be held for 60 to 90 seconds.

e. Immediately upon removal from the 10% sulphuric acid solution, spray rinse with deionized water for 10 to 15 seconds.

7.4.2 GOLD-STRIKE-PLATING PROCEDURE

It is necessary to gold-strike the surface of the nickel-plated conductors before gold plating to enable the surface to better receive the final gold plating. The procedure for gold-strike plating is as follows:

a. While applying 6-volts to the cable conductors, dip the exposed conductors into the gold strike solution. The gold strike solution shall be 0.03 to 0.05 troy oz./gal. of gold, citric acid to a baume 10, with a pH 3.5. Dip time for the gold strike shall be for 30 to 60 seconds.

b. Immediately upon removal from the gold strike solution, spray rinse with deionized water for 10 to 15 seconds.

7.4.3 GOLD-PLATING PROCEDURE

The gold plating equipment and process used shall be at the option of the manufacturer, but the plated conductors shall meet the requirements established in specification MIL-G-45204. The following procedure shall be utilized in conjunction with Figure 1 to ensure proper bonding of the gold to the nickel-plated conductor:

a. Immediately upon removal from the deionized water rinse, dip the exposed conductors into the gold plating solution. Autronex "C". Apply current to the cable conductors calculated at 10 amps/ft.^{2}. Plate for approximately 10 minutes to achieve class 1, minimum thickness, of 50 micro inches.

b. Upon removal from the gold plating solution, spray rinse in deionized water for 30 to 45 seconds.

c. Dry the exposed plated conductors and the cable end with dry, filtered compressed air.

d. Place the cable in an air circulated oven for a minimum of 30 minutes. The oven temperature shall be 50°C plus or minus 5°C.

7.5 PROCESS VERIFICATION

The gold plating shall be smooth, adherent, and free from blisters, laminations, nodules, pits, discontinuities, and porosity. Inspection under a magnification of 5X power should be used to identify these defects. The line of demarcation between gold-plating and nickel-plated areas shall be even and smooth.

7.5.1 SAMPLING AND TEST

Test specimens of the stripped cable (taken from a production inspection lot) shall be plated to a minimum thickness of 0.000050 inch and evaluated for thickness, adhesion, and corrosion resistance tests, as described in the following:

a. Thickness of the gold plate shall be a minimum of 0.000050 inch, unless otherwise specified. A section taken on a sample basis should be micro-photographed for measurement purposes.

b. A plated sample shall show no evidence of gold plate separation from conductor, after bending 180 degrees around a 1/8 inch rod. Each time the plating solution is renewed or re-charged, a sample shall be plated before actual production begins, checking for

7.5.1 SAMPLING AND TEST (Continued)

adhesion quality.

c. A gold-plated conductor sample shall evidence no corrosion of base metal after 2 hours of salt spray, in accordance with Federal Test Method Standard No. 151, Method No. 811.1.

FIGURE 1. PROCESS FLOW SEQUENCE FOR GOLD PLATING
FCC NICKEL COATED CONDUCTORS

Pre-Plating Examination
Contamination Removal

↓

Electrical Connection
FCC to Plating Cathode Rod

↓

Alkaline Clean
Cathode-6 volts-max. 20 sec.

↓

Spray Rinse-Deionized Water
30 to 45 sec.

↓

Cathodic Activate
ACS Sulphuric Acid, 10% solution
Chemical lead Anodes - 6 volts
60 to 90 sec.

↓

Spray Rinse-Deionized Water
10 to 15 sec.

↓

Gold Strike
Gold 0.03 to 0.05 Troy oz./gal.
pH 3.5 - Baume 10
30 to 60 sec.

Spray Rinse-Deionized Water
10 to 15 sec.

↓

Gold Plate
Autronex "C" - 10 amps/$ft.^2$
Approx. 10 minutes 50 micro inch

↓

Spray Rinse - Deionized Water
30 to 45 sec.

↓

Air Dry
Filtered Compressed Air

↓

Oven Dry
30 min. 50° C.

↓

Post Plating Examination
Plating Quality

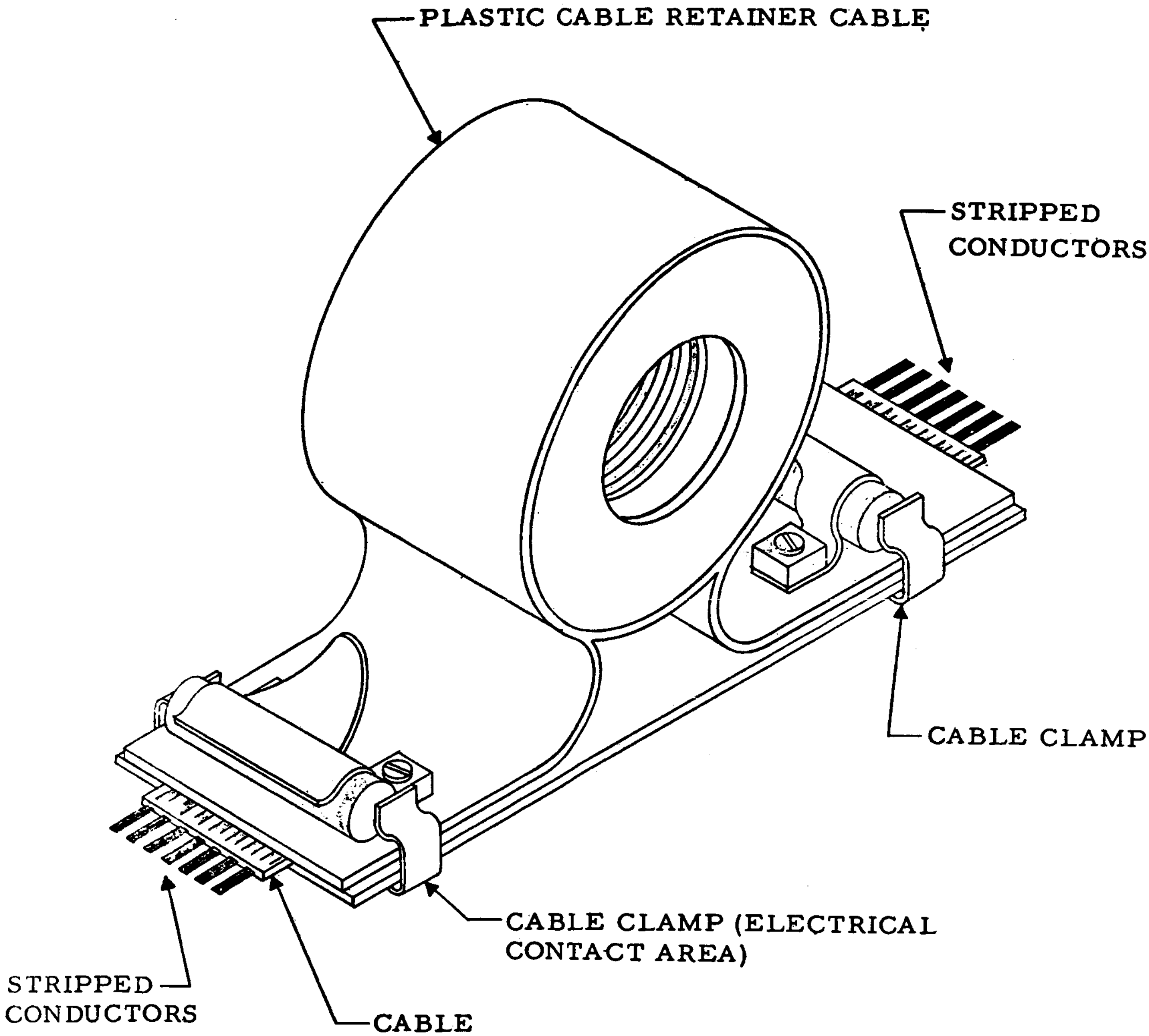


FIGURE 7-2 NASA/MSFC PLATING RACK WITH CABLE

SECTION 8
CONNECTOR ASSEMBLY

8.1 GENERAL

This section describes the procedures and process controls relative to assembly of both premolded rectangular plugs and molded-on cylindrical plug assemblies. Elements relative to cable stripping and conductor plating are contained in Sections 6 and 7 of this document, and should be referred to, prior to connector assembly operations.

8.2 PROCESS CONTROL REQUIREMENTS

Prior to performing the assembly of any connector, verify that all cable has been sheared, stripped, and plated in accordance with the previous process requirements. Visually examine each connector and associated hardware to assure that the contacts (when applicable), finish, seal, conductor spacer, insert, keys, wedge, and insulators are not damaged, and are free of foreign material, grease, dirt, etc. Check the seal insertion area for imperfections such as mold flash, cuts, gouges, or obvious damage to the sealing area of the connector.

8.2.1 CONNECTOR PROTECTION

All connectors shall have caps or other protective devices installed throughout all stages of fabrication and testing, except when connected with mating connectors, or during individual connector testing. When caps are removed for testing, cleaning, etc., the caps shall be replaced promptly after the operation is completed.

8.2.2 CONNECTOR CLEANING

Prior to assembly of a connector, all components and the inside surface of the connector shall be kept free of oil, dirt, grease, and other foreign material. If present, these substances shall be removed by wiping with a clean lint free cloth, dampened with a suitable cleaning solvent, followed by wiping with a clean dry cloth. Also, a clean soft brush may be used to remove loose contaminate on seals.

8.3 PREMOLDED RECTANGULAR PLUGS

Premolded rectangular plugs are utilized for 1.0, 1.5, 2.0, 2.5, and 3.0-inch wide cables, and are composed of parts that require no additional molding. Figures 1 and 2 illustrate a typical cross-section of the premolded rectangular plug assembly, together with details which define the parts required. The rectangular plugs are tabulated for cable conductor widths of 0.040-inch, with conductors spaced on 0.075-inch centers. Premolded rectangular plugs may be modified to accept cable conductor widths of 0.115-inch and conductors spaced on 0.150-inch centers. Modification of the plugs, to accept the larger conductors, shall be performed as described in paragraph 8.3.1, prior to plug assembly per the standard procedures described in paragraph 8.3.2.

8.3.1 PREMOLDED PLUG MODIFICATION

Modification of standard premolded rectangular plugs may be performed to accept cable conductor widths of 0.115-inch and conductors spaced on 0.150-inch centers. The modification is performed by removing the insulation barriers, as required, on the conductor spacer, wedge, and housing components of the plug (Reference Figure 1). Upon completion of the modification process, the plug and flat-conductor cable may be assembled as described in the following paragraph.

8.3.2 PREMOLDED PLUG ASSEMBLY

Preparatory to plug assembly, the operator shall assure that the cable conductors have been stripped to a 0.500 $\pm$ 0.005-inch length using the appropriate procedure described in Section 6, and that the conductors have been properly plated as described in Section 7 of this document. After the stripping and plating procedures have been verified, the selected plug assemblies shall be fabricated using Figures 1 and 2, and the following procedure.

a. Thread stripped conductors (both cables) through central opening of base plate. Move base plate back on cabling far enough to give liberty in working with each strip.

8.3.2 PREMOLDED PLUG ASSEMBLY (Continued)

b. Position conductors of both cables into slots of conductor spacer, moving the stripped margin of insulation against the base of the conductor spacer ribs. Apply a small amount of adhesive (MSFC 222, Type V) to the wedge prior to insertion.

c. Clamp conductor spacer and cable in folding tool and bend conductors at a 90 degree angle across the wedge groove.

d. Fold the conductors into the conductor spacer groove utilizing the folding tool.

e. Thread conductor spacer through housing, making sure that it is seated well into the housing.

f. Move base plate into position in the housing.

g. Insert locking keys and twist ears of each key as illustrated in Figure 2.

h. Pot base of plug with potting compound per procedures described in paragraph 8.5.

i. Apply a thin film of silicone primer (GE-554004 or equivalent) into the seal groove of plug housing, and allow to cure.

j. Apply a thin film of adhesive (GE-RTV118 or equivalent) into the seal groove of the plug housing.

k. Install the silicone rubber seal into the groove. Make sure that the seal is seated properly.

8.3.3 PREMOLDED PLUG PROCESS VERIFICATION

Examine the completed plug to assure that all provisions of this document and applicable engineering documents are complied with. Particular care shall be exercised during the assembly operation to insure reliability. The following precautions are provided for specifying those inspection points necessary in the assembly of a premolded plug-flat cable assembly:

a. The operation of threading the conductors into the plug is particularly critical. Care must be taken not to damage the conductors during the insertion process. Any bends, kinks, or scratches should be cause for rejection if they affect proper seating of the conductors in the grooves of the plug.

8.3.3 PREMOLDED PLUG PROCESS VERIFICATION (Continued)

b. Check to assure that the cable stripline aligns with the inside edge of the plug.

c. Inspect the conductors, after folding, for separation of plating around the area of the fold.

d. Before potting verify plug keys are secured properly.

e. The potting compound in the base of the plug should be checked for quality as described in paragraph 8.5.8.

f. Inspect for excessive adhesive around or on the seal and for proper cure.

8.4 MOLDED-ON CYLINDRICAL PLUGS

Molded-on cylindrical plugs are utilized for 0.25 and 0.5-inch-wide cable. The plug assembly consists of coupling ring, window piece, conductor spacer, insulator, shell, and insert, which are assembled and molded together to form an integrated assembly. In addition, the assembled plug is potted and a seal is cemented into a groove on the plug face to seal the junction between plug and receptacle. Figures 3 and 4 illustrate a typical cross-section of the complete plug assembly, together with details which define the parts required.

8.4.1 MOLDED-ON PLUG ASSEMBLY

Preparatory to plug assembly, the operator shall assure that the cable conductors have been stripped to 0.470 $\pm$ 0.005-inch length using the appropriate procedure described in Section 6, and that the conductors have been properly plated as described in Section 7 of this document. After the stripping and plating procedures have been verified, the selected plug assembly shall be fabricated using Figures 3 and 4, and the following procedure:

a. Insert the conductors through their respective openings (beveled side) of the window piece.

b. Separate conductors of one cable from those of the other cable, and insert the conductor spacer into the window piece.

c. Clamp the conductor spacer and cable in folding tool and bend conductors at a 90 degree angle across the wedge groove.

8.4.1 MOLDED-ON PLUG ASSEMBLY (Continued)

d. Fold the conductors into the conductor spacer groove utilizing the folding tool.

e. Remove spacer and folded cables from folding tool.

f. Press insulator into the conductor spacer groove and trim the insulator flush with the sides of the conductor spacer.

g. Mold the insert around the assembled parts. The suggested molding procedure is given below. Molding temperatures and pressure shall be applicable to manufacturer's instructions:

   1. Install proper mold halves into the molding machines and heat the mold.
   2. Load hopper with dry molding material, and heat the material.
   3. Purge machine, and charge cylinder with approximately 20 percent more material than is required for the part.
   4. Insert cable spacer, and place the assembled parts properly in the lower mold half.
   5. Close the mold-halves and apply pressure. Hold the pressure for 15 to 20 seconds.
   6. Release pressure and recharge cylinder.
   7. Allow 40 to 50 seconds cooling time between pressure release and opening of the mold halves. (Cycle requires approximately 1 minute.)
   8. Open mold halves about 0.5 inch and pull bottom insert out. Open mold halves more to eject the molded part, and remove molded part from machine.

h. Remove cable spacer from between cables and trim sprues from molded plug body.

i. Dimple shell with a spring-loaded punch to keep shell on molded body. Dimples must be 120 degrees apart and 0.09-inch from front rim of shell.

j. Pot base of plug with potting compound per procedures described in paragraph 8.5.

k. Apply a thin film of silicone primer (GE-554004 or equivalent) into the seal groove of plug housing, and allow to cure.

8.4.1 MOLDED-ON PLUG ASSEMBLY (Continued)

l. Apply a thin film of adhesive (GE-RTV118 or equivalent) into the seal groove of the plug housing.

m. Install the silicone rubber seal into the groove. Make sure that the seal is seated properly.

8.4.2 MOLDED-ON CYLINDRICAL PLUG PROCESS VERIFICATION

Examine the completed plug to assure that all provisions of this document and applicable engineering documents are complied with. Particular care shall be exercised during the assembly operation to ensure reliability. The following precautions are provided for specifying those inspection points necessary in the assembly of a molded-on cylindrical plug-flat cable assembly:

a. The operation of threading the conductors into the plug is particularly critical. Care must be taken not to damage the conductors during the insertion process. Any bends, kinks, or scratches should be cause for rejection if they affect proper seating of the conductors in the windows.

b. Inspect the conductors, after folding, for separation of plating around the area of the fold after each operation.

c. Verify that molding operation has been properly performed as described in steps g-1 through g-8 of paragraph 8.4.1.

d. The potting compound in the base of the plug should be checked for quality as described in paragraph 8.5.8.

e. Inspect for excessive adhesive around or on the seal and for proper cure.

8.5 POTTING ENCAPSULATION

The procedures described in the following paragraphs are to be used in potting plug assemblies with elastomeric compounds. The criteria conforms to, and shall be used in conjunction with all requirements of procedures MSFC-SPEC-222 and MSFC-PROC-196, for using epoxy resin compounds.

8.5.1 PROCESS CONTROL REQUIREMENTS

Prior to the potting operation, verify that the plug assembly bears evidence of inspection acceptance for compliance to design requirements and

workmanship. Care shall be taken to assure that all foreign material, such as dirt, oil, or grease, has been removed from the plug and cable areas to be potted. If contaminants are present, they shall be removed by wiping with a clean lint-free cloth, dampened with a suitable cleaning solvent, followed by wiping with a clean dry cloth.

8.5.2 CONTROL AND CLEANLINESS OF POTTING FACILITY

The potting facility shall be isolated from such contaminants as dust, metallic particles, water, oil, and grease. Bench tops shall be protected from spillage by disposable coverings, and floors shall be cleaned frequently with an acceptable cleanser. The temperature of the potting facility shall be maintained at 24 $\pm$ 2 degrees Celsius; and the relative humidity shall not exceed 55 percent. Adequate ventilation shall be provided to accommodate the volume of compounds, solvents, and primers being used. Forced-draft ventilation, where toxic fumes are generated, is necessary and fumes shall be drawn away from the operator and vented to the outside.

8.5.3 EQUIPMENT

The potting area should be equipped with air pressurization equipment capable of delivering moisture-free air (maximum 90 psig), and a vacuum system capable of producing a differential pressure for removing trapped air from the potting compound. Accurate weighing equipment shall be provided for measuring the potting constituents. The injection gun shall be either a manual or air-operated calking gun equipped with a disposable plunger, liner, and nozzle. In addition, holding racks should be available to hold the harness components rigid and in proper alignment.

8.5.4 HANDLING PRECAUTIONS

All personnel that are engaged in potting encapsulation shall demonstrate proficiency in producing high quality end items, and be trained in proper handling procedures. In general, the chemicals involved are safe when properly handled by trained and qualified personnel, but when carelessly handled, the materials utilized for potting may cause severe physiological reactions. The

8.5.4 HANDLING PRECAUTIONS (Continued)

following criteria shall be implemented, in conjunction with manufacturer's instructions, to insure safe handling procedures:

a. Avoid contact with solvents, primers, and compounds with the skin. Protective clothing shall be changed when soiled by potting materials, and shall be laundered prior to reuse. Special care shall be taken to prevent contact with open breaks on the skin.
b. Avoid ingestion and inhalation of vapors.
c. If the eyes are accidentally contaminated, flush with water and obtain medical attention immediately.
d. Areas of the skin exposed to solvents, primers, and compounds shall be cleaned with an approved cleaner and then with a nonabrasive soap and clean water. Personnel shall not smoke or eat until after thorough cleansing of exposed skin areas.
e. No smoking or open flames shall be allowed within 25 feet of an operation where compounds, primers, and solvents are being used. "NO SMOKING" signs shall be displayed in conspicuous places.
f. Cosmetics and hand creams shall not be used by the operators.

8.5.5 PLUG AND CABLE PREPARATION

To insure proper adhesion of the potting compound to all components, the plug, cable, and all other materials that will contact the compound must be clean and free from any trace of contaminants. Caution must be exercised during cleaning to insure that cable insulation and plug components are not exposed to cleaning solvent to the extent that swelling or other indications of damage occur. Upon completion of cleaning, primer shall be applied to the cable insulation 0.125 $\pm$ 0.06-inch above the area to be covered with the potting compound and to all surfaces of the plug coming into contact with the potting compound. The primer shall be cured in accordance with manufacturer's instructions.

8.5.6 POTTING COMPOUND PREPARATION

Prior to preparing the potting compound, verify that the resin and activator have been successfully acceptance tested and that the shelf life has not expired. The following procedures should be followed in preparing the compound for application:

8.5.6 POTTING COMPOUND PREPARATION (Continued)

a. Place the resin and activator (in the proper proportional ratios) in a clean, dry, nonporous container having at least four times the capacity as the volume of the combined parts. Blend the resin and activator thoroughly by mechanical agitation or by stirring with a clean spatula. Avoid fast stirring that may entrap excessive air.

b. Place the container in a vacuum chamber and apply a vacuum. Maintain the vacuum until foaming subsides, but not more than 10 minutes.

8.5.7 POTTING REQUIREMENTS

The potting process shall conform to all requirements of MSFC-PROC-196; facilities, equipment, safety precautions, personnel proficiency, and process controls shall be fully complied with. Upon verification of the preceding requirements the potting process shall be performed as described in the following procedure:

a. Transfer the mixed compound from the mixing container to the injection gun cartridge by carefully and slowly pouring the compound down the side of the cartridge, using care not to entrap air, until the desired level in the cartridge is reached. Put the plastic plunger in place and insert the cartridge into the gun. Attach the correct size nozzle for the applicable potting job and adjust the air pressure supply to approximately 15 psig.

b. Test the injection gun for free and even flow of compound from the nozzle.

c. Prepare a hardness test sample from each mixed batch by using a small container to make a "button" of the compound (approximately 1 inch in diameter by 0.750 inch thick). Cure according to the same schedule assigned to the job it is taken from. The button shall accompany the connector throughout the remainder of the cure cycle.

d. Position the nozzle at the center of the plug and start the flow of the compound.

e. Start the flow of the compound, assuring an even flow.

f. Keep the nozzle tip at the swell level and continue the injection until the required level is attained. Let the compound settle a minimum of 5 minutes and replenish to the required level.

g. Cure the potting compound as recommended by the manufacturer.

8.5.8 EXAMINATION OF POTTING

The potted plug assembly shall be examined for general appearance and quality of workmanship. The surfaces of the potted area shall be free from voids, blisters, tackiness, soft spots, cracks, discoloration, lumps, non-adherence, or any defect indicative of low quality resin or poor workmanship. The hardness of the resin shall be determined by three readings, using the D scale of a Shore Durometer, or equivalent. The readings shall be made on a flat surfaced sample "coupon" prepared and processed per MSFC-PROC-196.

CAUTION: Care shall be used in handling and examination of assemblies potted with epoxy resins. The rigid, sharp edges of the cured resins may cut, mar, or mutilate the cable assembly if the cable is forcefully handled.

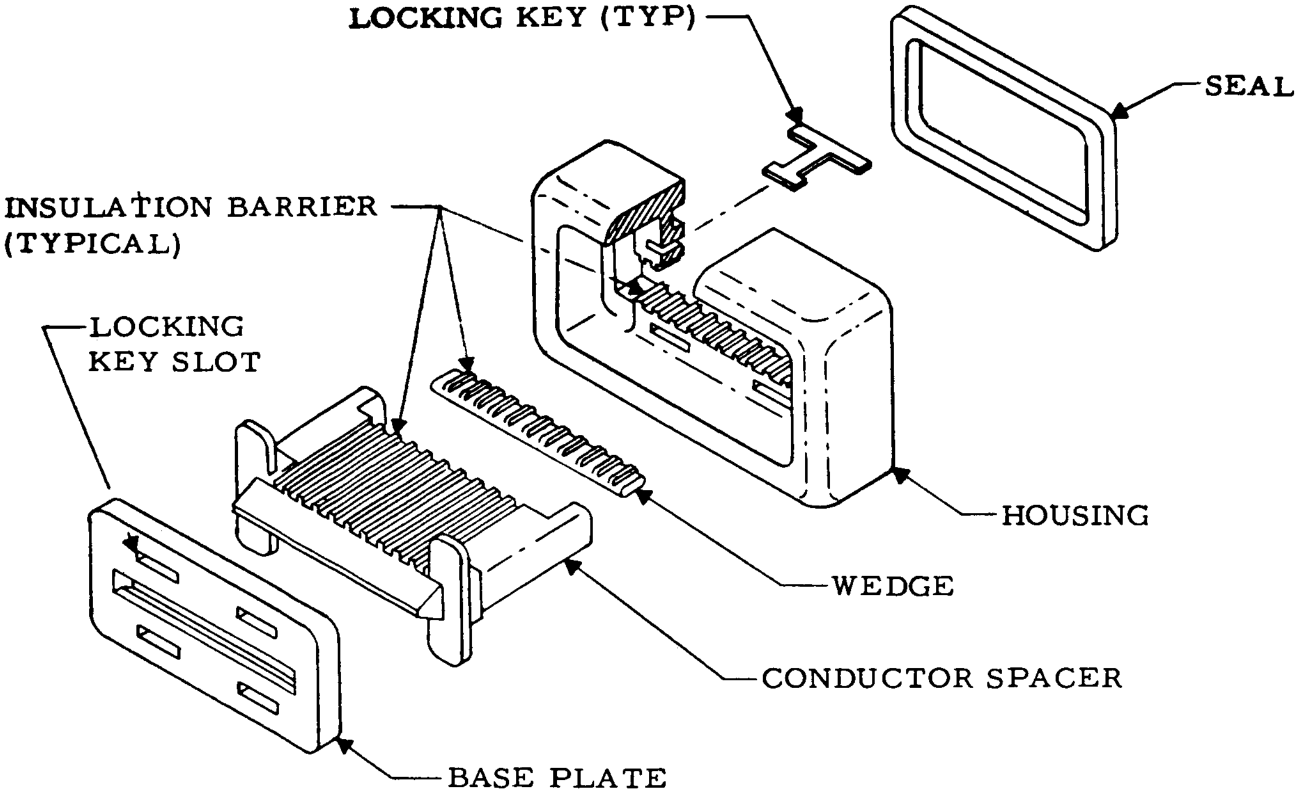


FIGURE 8-1 TYPICAL PREMOLDED RECTANGULAR PLUG PARTS

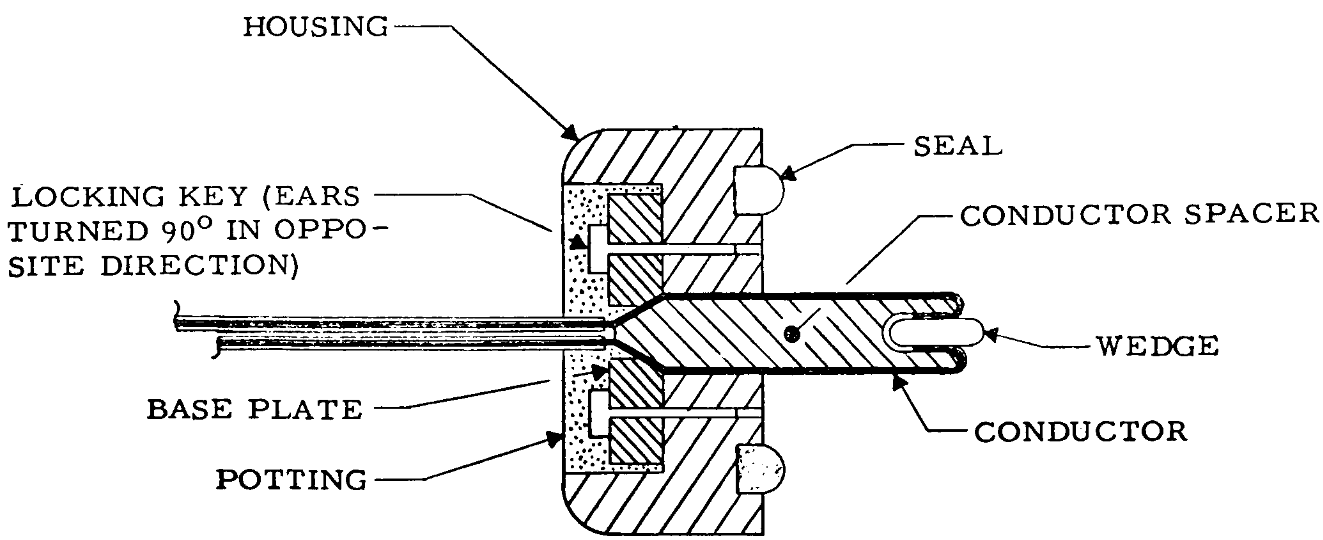


FIGURE 8-2 PREMOLDED RECTANGULAR PLUG (SECTION)

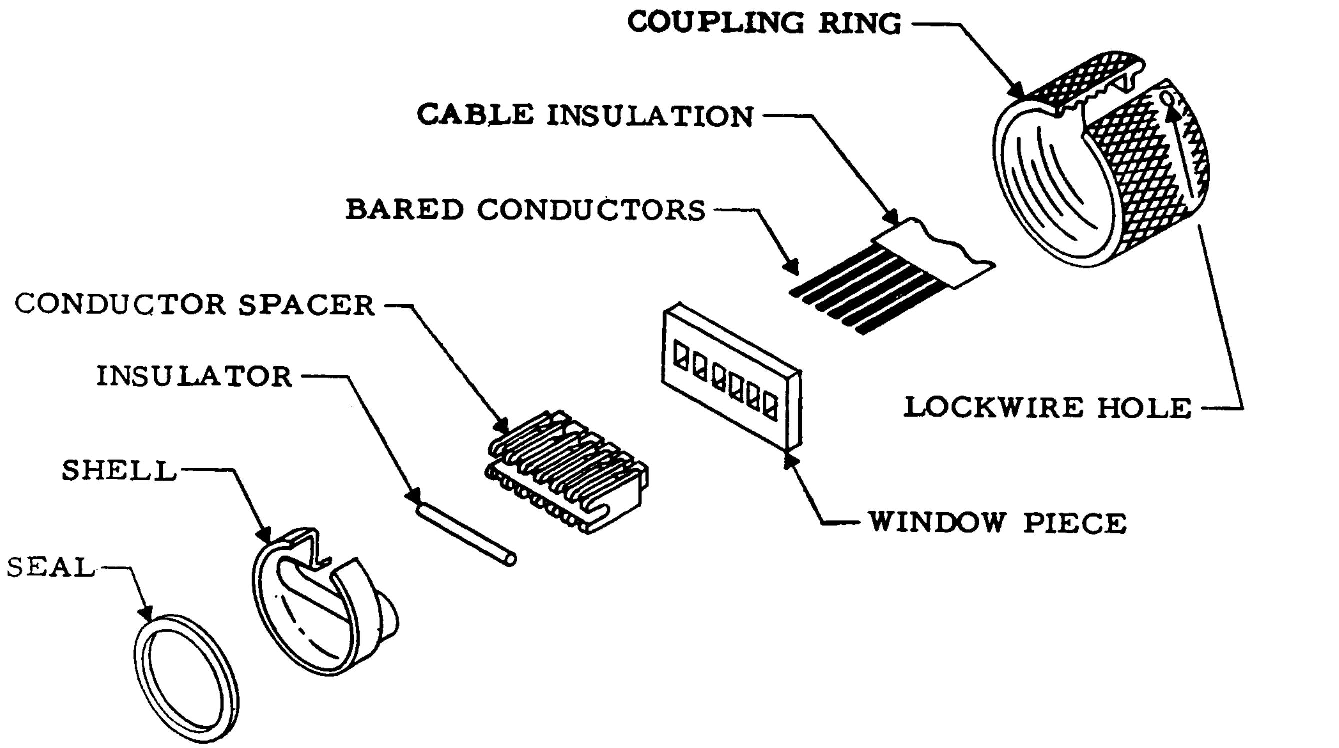


FIGURE 8-3 CYLINDRICAL PLUG PARTS

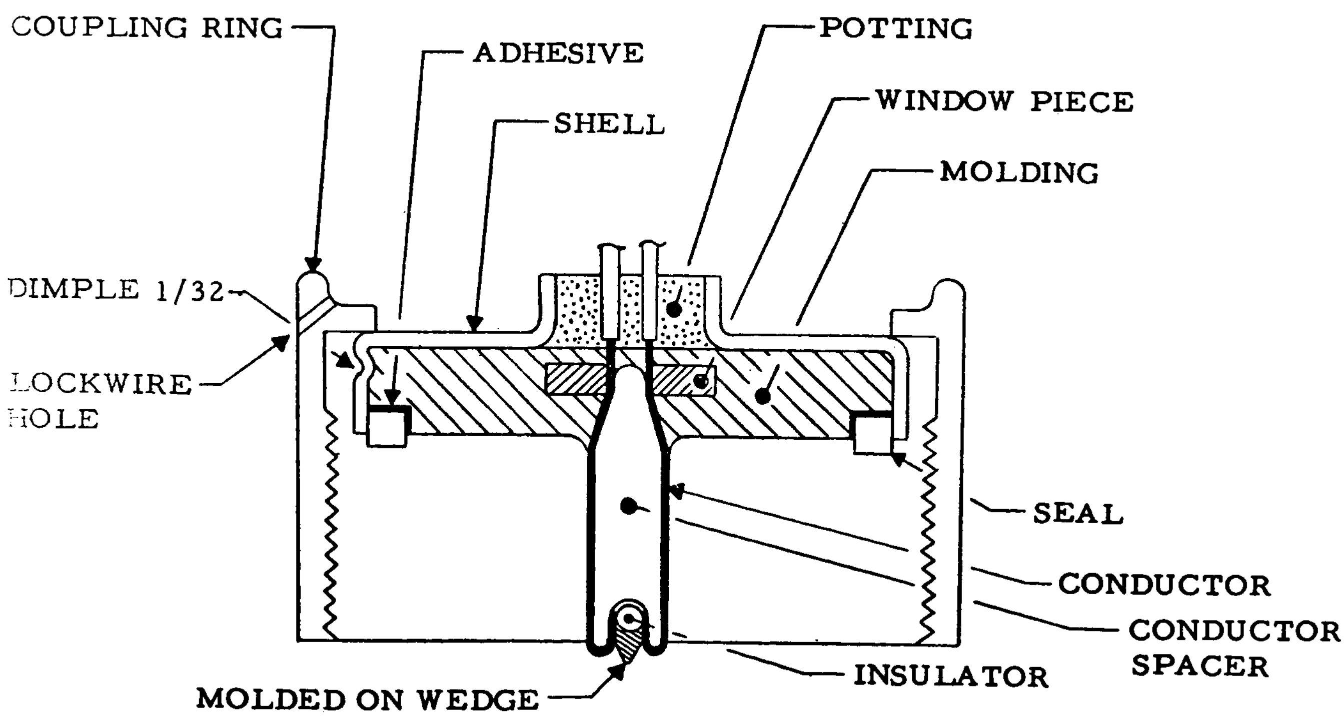


FIGURE 8-4 CYLINDRICAL PLUG (DIMPLED)

SECTION 9

HARNESS IDENTIFICATION

9.1 GENERAL

This section defines the requirements for both temporary and permanent identification of flat-conductor cable harness assemblies and connectors, including the criteria for temporary markings that are necessary to facilitate harness installation.

9.2 TEMPORARY HARNESS IDENTIFICATION

Temporary identification for scheduling and process control which is not required for the finished assembly is permissible. Such identification markers shall not adversely affect the assembly, and shall not appear on the completed harness.

9.2.1 TEMPORARY IDENTIFICATION METHODS

Tagging may be used to temporarily identify harnesses, although identification-marking-by-packaging shall be used in preference to tagging for harnesses which can be placed in a package conveniently. When used, tags shall be of cloth or pressed fiber, and shall be legibly marked by impression stamping or other permanent method using characters at least 3/32 inch high. Tags shall be securely attached to the harness with cord, or by wrap around in a manner that will not damage the assembly in processing, shipment, or storage. Application of adhesive tags is not recommended due to the possibility of harness contamination.

9.3 PROCESS CONTROL

Before application of the permanent harness and connector identification markings, verify that the harness assembly complies with the applicable sections of this document, and design engineering requirements. Verify that the harness configuration and temporary harness identification agree with the design engineering drawings, and connector "P" (plug) numbers are correct. After removal of the temporary identification markers, verify that harness surface is not contaminated or damaged such as cuts, nicks, or abraded areas.

9.4 IDENTIFICATION CRITERIA

The combination of letters and numbers which constitute the identification code shall be in accordance with design engineering drawings. Unless otherwise specified on the applicable drawings, identification shall be applied directly to a piece of insulated sleeving or a band marker, as applicable. Application of identification shall not cause damage to the sleeve or marker, and the identification shall be applied so that it cannot be readily rubbed off. Identification markers shall withstand the same temperatures and other environmental conditions to which the harnesses are subjected.

9.4.1 HARNESS ASSEMBLY IDENTIFICATION

The harness reference designation and part number shall be stamped on a band marker or insulated sleeve as described in the applicable procedures and as illustrated in Figure 1. The marker or sleeve shall be placed as close as possible to the lowest alpha numbered connector (i.e., "P1") on the harness, but not more than 12 inches from the connector.

9.4.2 CONNECTOR IDENTIFICATION

A band marker or insulated sleeve marked with the applicable connector reference designation and mating part reference designation, shall be located adjacent to each connector as illustrated in Figure 2.

9.4.3 ACCESSIBILITY

The identification shall be installed so that it is readable from the normal point of observation. Specifically, if there is a choice of installing the identification "upside down" or "right side up" from the normal point of observation, the identification should be installed "right side up". The numbers may read either toward or away from the terminated end of the harness. An objective shall be to position all identification markers on the harnesses so as to provide maximum visibility after installation. Every effort shall be made to locate identification so that clamps, support devices, etc., do not have to be removed, or the harness twisted, in order to read the identification.

9.4.4 LEGIBILITY

All identification characters shall be legible, permanent, and colored (where applicable) to contrast with the surface on which the identification

9.4.4 LEGIBILITY (Continued)

is placed. The characters shall be of sufficient size and color to provide ease of identification through fabrication, checkout, and mission duration.

9.5 IDENTIFICATION OF HARNESSES

All harness assembly identification criteria shall be marked by direct application on band markers or by means of a stamped piece of sleeving. Regardless of the method selected, an attempt shall be made to use the same method for all identification purposes so that uniformity can be maintained. All identification markers shall be firmly secured to the harness so as to prevent loss of markers from shock, vibration, etc.

9.5.1 MARKING EQUIPMENT

Band marker and sleeve identification marking shall be accomplished with calibrated marking machines as specified in the applicable process specification or manufacturer's instructions for detailed calibration and operation of the machine. Marking shall be performed utilizing a marking machine with automatic foil and work feeds (optional), adjustable pressure and dwell time. Marking materials (such as foils, inked ribbons, etc.) shall be selected to correspond with the base material being identified.

9.5.2 MARKING PROCESS CONTROL

Prior to hot impression marking of the identification bands and sleeves, assure that:

1. Band marker or sleeving is free of dust, grease, or other foreign matter.
2. The correct size of type is selected per the manufacturer's instructions. Flat faced type shall be used for marking identification plates, bands, and sleeving not supported by a mandrel.
3. Marking machine has received periodic inspection and maintenance at intervals that will assure that the machine and accessories are in good operating condition. Marking foil is the correct type required for the type sleeving or band material to be marked.

9.5.3 APPLICATION

Identification shall be imprinted on band markers or sleeves using an approved method which will not impair the quality of the marker or sleeve.

9.5.3 **APPLICATION (Continued)**

When the **direct stamping process is used for band markers or sleeve identification, the following procedure shall be used:**

a. **Regulate the pressure, indicated type temperature, and dwell time for each material to provide maximum transfer of pigment from foil to the material being imprinted, and for best legibility. Use the lowest pressure and shortest dwell time that will produce a legible and permanent imprint, to prevent penetration of the type through the material.**

b. **Use characters of sufficient size and machine adjustments necessary to provide markings for best legibility.**

c. To prevent uneven depth marking, make sure that type faces are clean and that all characters are set in the same plane. Plated and unplated type may be of different depths and should not be used together.

9.5.4 STAMPED INSULATION SLEEVE IDENTIFICATION METHOD

Harness identification criteria may be applied by affixing marked, non-metallic sleeves imprinted with the applicable identification data. Sleeving material shall withstand the same temperatures and other environmental conditions to which the wire harness is subjected. When the harness identification criteria is applied utilizing sleeves, the following procedure shall be used:

a. Select the correct size sleeve to fit over the harness. Where possible, the sleeve should be snug enough so that subsequent string ties are unnecessary.

b. Apply the identification markings to the sleeve using the direct stamping application procedure described in paragraph 9.5.3.

c. **Cut the sleeving so that each length includes a complete identification. The sleeve shall be no longer than necessary to include all identification information plus a margin for clarity.**

d. **Locate the identification sleeves on the wire harness as described for the applicable identification requirement.**

9.5.5 **BAND MARKER IDENTIFICATION METHOD**

Identification of harnesses may be accomplished by affixing marked, non-metallic band markers or identification plates imprinted with the applicable

9.5.5 BAND MARKER IDENTIFICATION METHOD (Continued)

identification data. All band markers, identification plates, and adjustable cable straps used for identification purposes shall meet design standard 40M39582. When harness identification criteria is applied utilizing band markers, the following procedure shall be used:

a. Select the desired size identification plate and strap (if required) to fit over the harness.
b. Apply the identification markings to the plate using the direct stamping application procedure described in paragraph 9.5.3. Flat-face type and foil must be used. More than one number, or row of numbers may be stamped on a single band marker.
c. Place the plate and strap(s) around the wire bundle and run strap tip through the hub. The ribs must be placed against the wire bundle. Pull the strap(s) tightly around the wire bundle by hand.
d. Tighten strap(s) using manufacturer's recommended tool and procedure, taking care not to damage the wire harness, and cut excessive strap length.

9.6 LOCATION MARKER IDENTIFICATION

Non-metallic identification markers may be installed on the harness assemblies to reference and identify specific locations during harness installation. Band markers or insulated sleeves shall be stamped with applicable stringer, station, frame, aximuth, grid, or plane location markings, and located on the harness to aid in installation and configuration control.

9.7 IDENTIFICATION PROCESS VERIFICATION

Visually examine the final harness and connector identification markings to assure that:

a. The identification marker material is of the correct type and style.
b. The identification marking agrees with applicable engineering drawing.
c. Lettering or numbering is legible.
d. Identification markers are located properly.

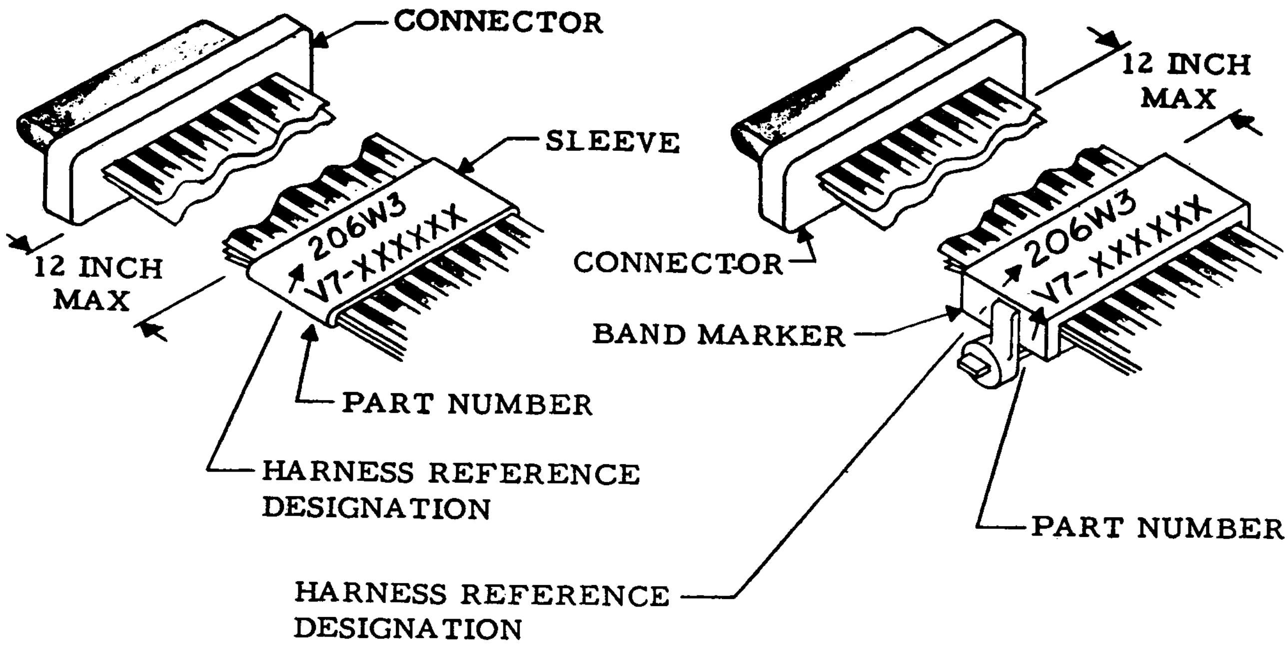


FIGURE 9-1 IDENTIFICATION OF HARNESS ASSEMBLY

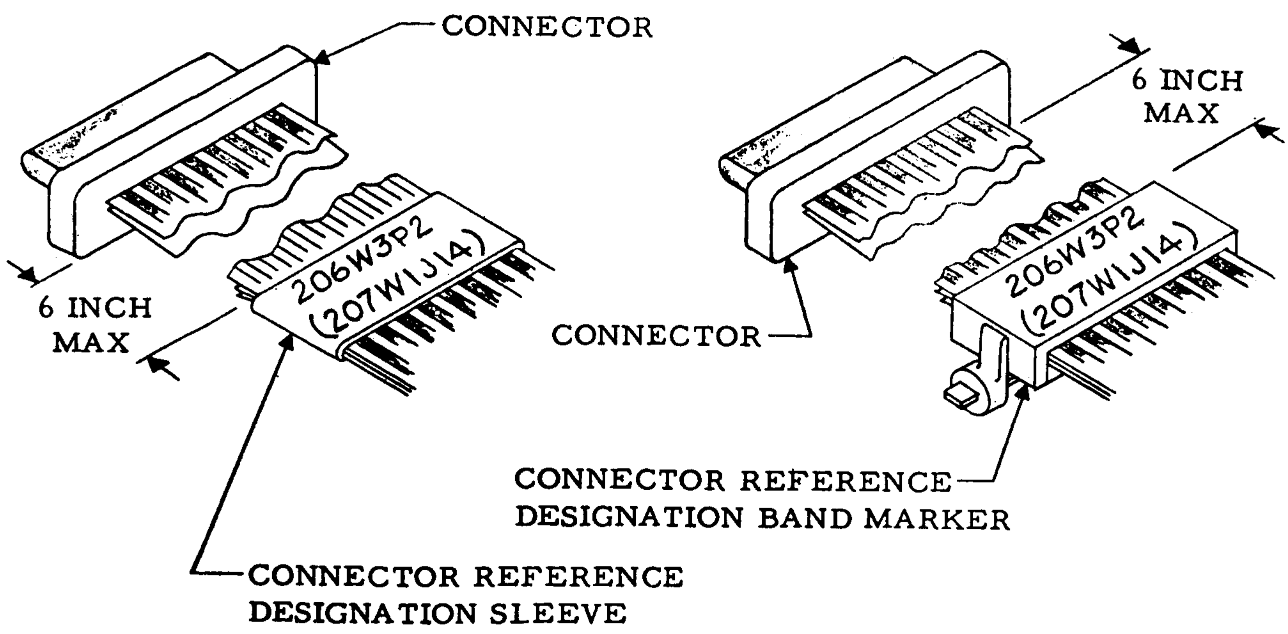


FIGURE 9-2 IDENTIFICATION OF CONNECTOR PLUGS

SECTION 10

HARNESS CLEANING

10.1 GENERAL

This section establishes the procedure for cleaning flat conductor cable harness assemblies, after completion of final fabrication and test. The cleaning procedures outlined in the following paragraphs shall be used in conjunction with the handling and packaging criteria contained in Section 11.

10.2 PROCESS CONTROL REQUIREMENTS

Prior to cleaning, assure that the harness assembly has successfully met all previous quality and design requirements. Visually examine the assembly to assure that flat conductor cable and connectors are free of damage, and that the harness is properly identified. In addition, verify that the facility environmental controls are within requirements stated in the following paragraphs, prior to start of cleaning.

10.2.1 FACILITY REQUIREMENTS

Final harness cleaning and sealing shall be accomplished in a class 100,000 level clean room that complies with the intent of MSFC-STD-246A. The temperature shall be +68°F to +78°F, and relative humidity shall be 60%, or less, if necessary to preclude condensate forming. The garment requirements shall be coveralls, caps, and shoe covers, and the handling of the harness during cleaning operations shall be performed with clean, lint-free gloves. Records shall be maintained of the facilities environmental levels, with daily checks of temperature and humidity, and a minimum of three times a week for airborne particulate. Daily checks shall be performed to assure positive pressure differential and air flow of at least 40 FPM.

10.3 CLEANING OF HARNESS ASSEMBLIES

Completed harness assemblies shall be cleaned with either isoprophyl alcohol (FED-SPEC-TT-I-735, Grade A) or ethyl alcohol (FED-SPEC-O-EO-760) to remove all contamination and foreign matter. Harnesses subjected to the outlined method of cleaning shall not be immersed in the approved cleaning solvent, and will not require any form of heat drying. Complex surfaces shall

10.3 CLEANING OF HARNESS ASSEMBLIES (Continued)

be blown clean with nitrogen per MIL-P-27401, Type I, or dry air that has been cleaned and dried in accordance with the procedures specified in MSFC-PROC-404, except hydrocarbon content shall not exceed 15 ppm by volume.

CAUTION: Use of other than the above cleaning agents and methods may result in degradation to the connector materials and possible damage to the cable insulation.

10.4 CLEANLINESS VERIFICATION

The cleaning procedure employed shall remove traces of oil, wax, gum, dust, dirt, fingerprints, organic soils, scale, corrosion, and other foreign materials as determined by visual examination using black and/or white light inspection. Scale-free discoloration and specific surface treatments shall not be considered visual contamination. During final cleaning, particles of dust which are observed under black light, but are not visible under white light, shall be removed by the use of a vacuum; any other foreign matter on the harness shall be cause for recleaning. Upon verification of cleanliness, the harness shall be tagged, sealed, and packaged, as described in Section 11 of this document.

SECTION 11

HARNESS HANDLING, PACKAGING AND SEALING

11.1 GENERAL

This section establishes and defines the methods and requirements for handling, packaging, and sealing of flat-conductor cable harness assemblies.

11.2 PROTECTION LEVEL CRITERIA

Flat-conductor cable harness assemblies require varying degrees of protection at all times. The performance and/or reliability of the assembly can be directly affected by the lack of adequate packaging or protection during in-process handling, storage, and shipment. Harness assembly protection shall be considered as the application of protective measures to prevent damage from physical and climatic environments during intra/inter facility handling, in-process, transportation, and storage operations.

11.3 APPLICATION

The appropriate level of harness protection shall be implemented by the manufacturing planning documents, and shall provide the necessary information required to assure adequate protection from the initial processing of the flat-conductor cable, through shipment of the finished harness assembly.

11.4 IN-PROCESS HARNESS ASSEMBLY HANDLING PROTECTION

Harness handling shall be done carefully and held to a minimum to reduce the possibility of connector damage and work-hardening, or fatigue of the cable. All connectors shall be protected with suitable snug-fitting plastic dust caps as illustrated in Figure 1, except when it is necessary to work directly upon them, or when mated. Conductor ends shall be protected as illustrated in Figure 2. Care is required in handling completed harness assemblies which have been cleaned and packaged to prevent damage or rupture of the outer wrap or packaging.

11.4.1 INTRA-INTER PLANT PROTECTION

Whenever harnesses are required to be transported to a service or repair area, they shall be packaged for shipment so that the harness does not become damaged. Connectors shall be individually wrapped with nylon bags and cushion material to prevent damage to themselves or other parts of the harness.

11.5 FINAL HARNESS ASSEMBLY SEALING AND PACKAGING

Prior to the sealing of the completed and cleaned harness assembly, assure that all design criteria and cleaning requirements have been performed and are acceptable. Verify that each connector is protected with a plastic cap and over-wrapped with a nylon bag.

11.5.1 HARNESS ASSEMBLY SEALING

Completed flat-conductor cable harness assemblies shall be coiled to form a loop of sufficient diameter whereby the cable will not be creased or permanently deformed. It is advisable to package harness lengths longer than 5 feet in a handling device similar to that shown in Figure 3. Assure that connectors are adequately protected and cannot damage the flat-conductor cable insulation. Additional cushion material may be installed at this time. Place the harness into a clean nylon bag, purge with dry nitrogen, and immediately heat seal; then overbag with antistatic polyethylene film, 6 mils thick and heat seal. Identify the sealed harness per paragraph 11.5.4.

11.5.2 HARNESS ASSEMBLY PACKAGING

Prior to packaging, assure that the sealed harness assembly wrapping is free of pin holes, tears, or cuts, loose or damaged closures, or broken cleanliness certification decals.

11.5.3 PROTECTIVE CONTAINERS

Select a suitable size cushioned container to place the harness into. The container construction and material shall be on such integrity to provide positive protection from physical and climatic environments during storage and transportation. The container size shall be selected so that the harness, or handling device containing the harness, generally fills the container, but does not interfere with closing of the container. Additional cushion material may be added to firmly hold the harness and prevent excessive movement.

11.5.4 IDENTIFICATION

Each cleaned and bagged harness assembly and container shall have an identification label or tag attached to the sealed harness (may be inserted between the nylon and polyethylene bag) and attached to the outside of the container, or inserted in the container, if the label or tag can be viewed from the outside. The tag or card shall carry the following information:

DRAWING/PART NUMBER______________________

E:O.______________________

SERIAL NUMBER______________________

INSPECTED BY:______________________

CONTRACT NUMBER______________________

"THIS HARNESS ASSEMBLY HAS BEEN CLEANED IN ACCORDANCE WITH______________________."

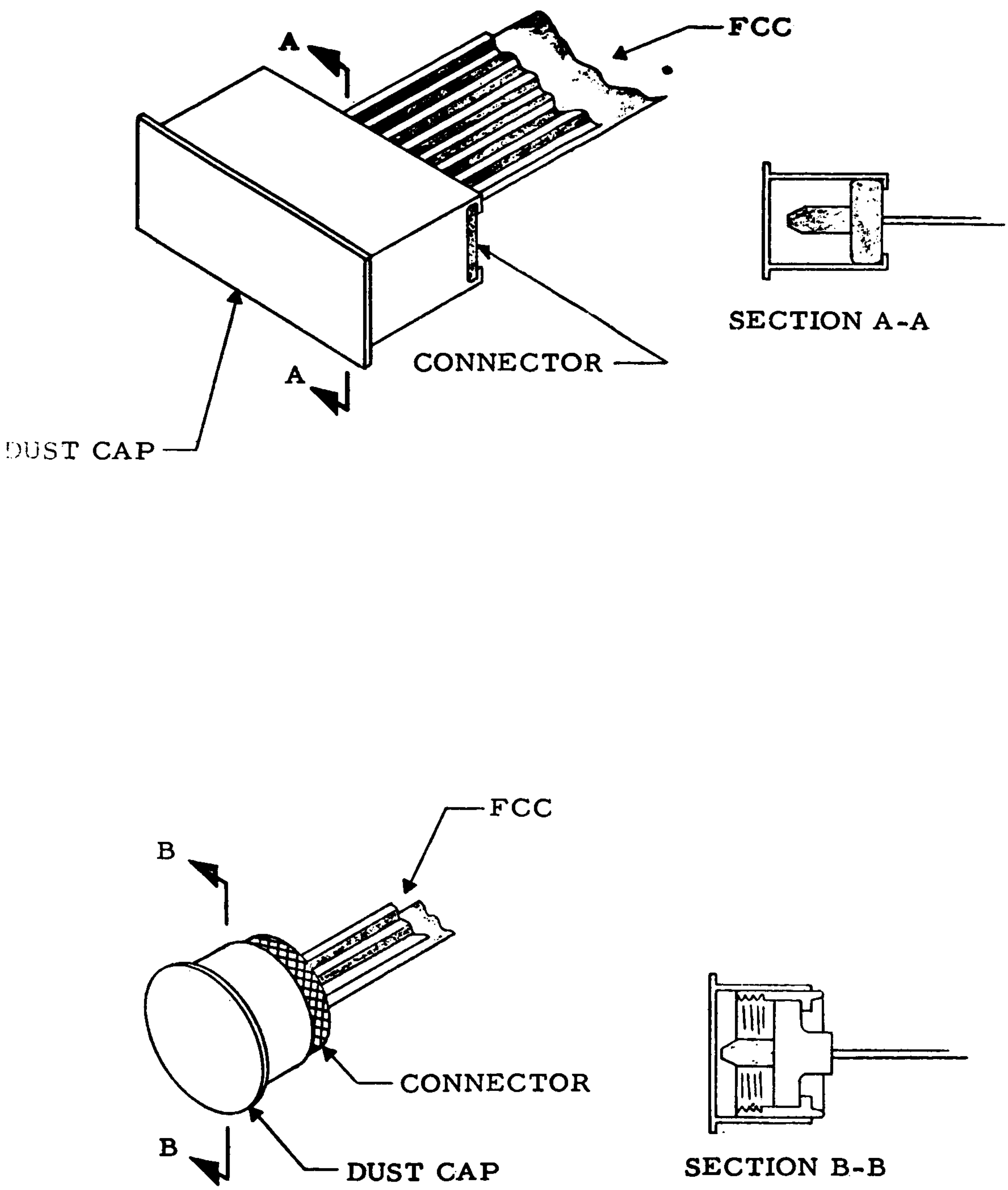


FIGURE 11-1 TYPICAL CONNECTOR DUST CAPS

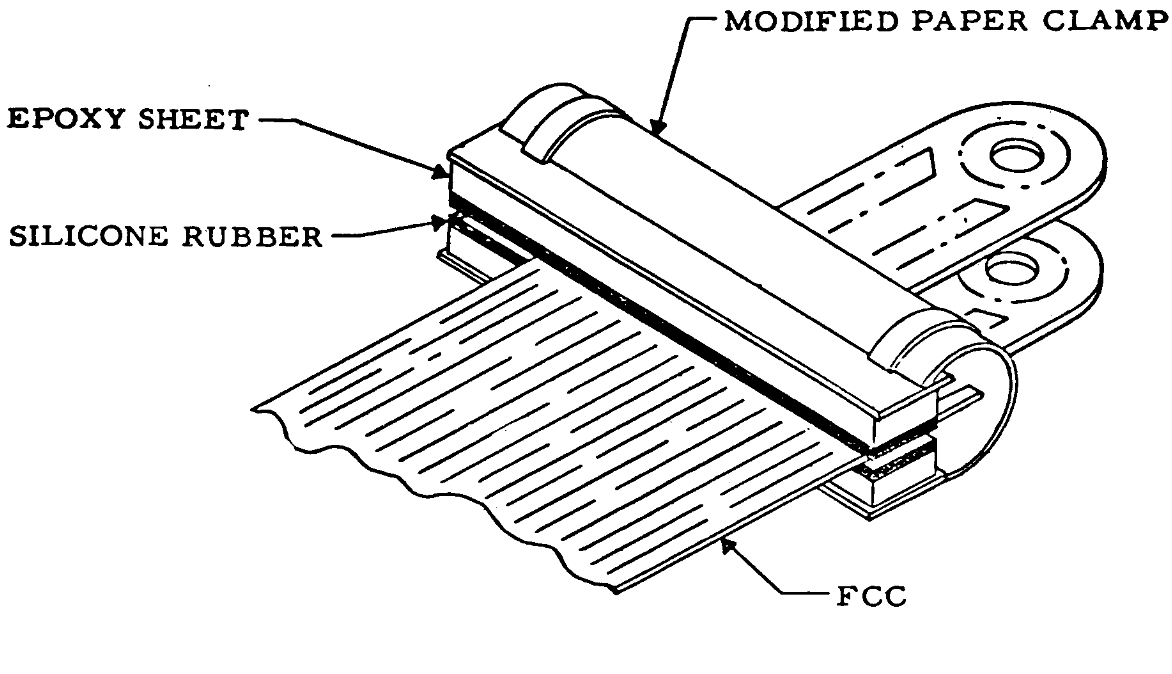
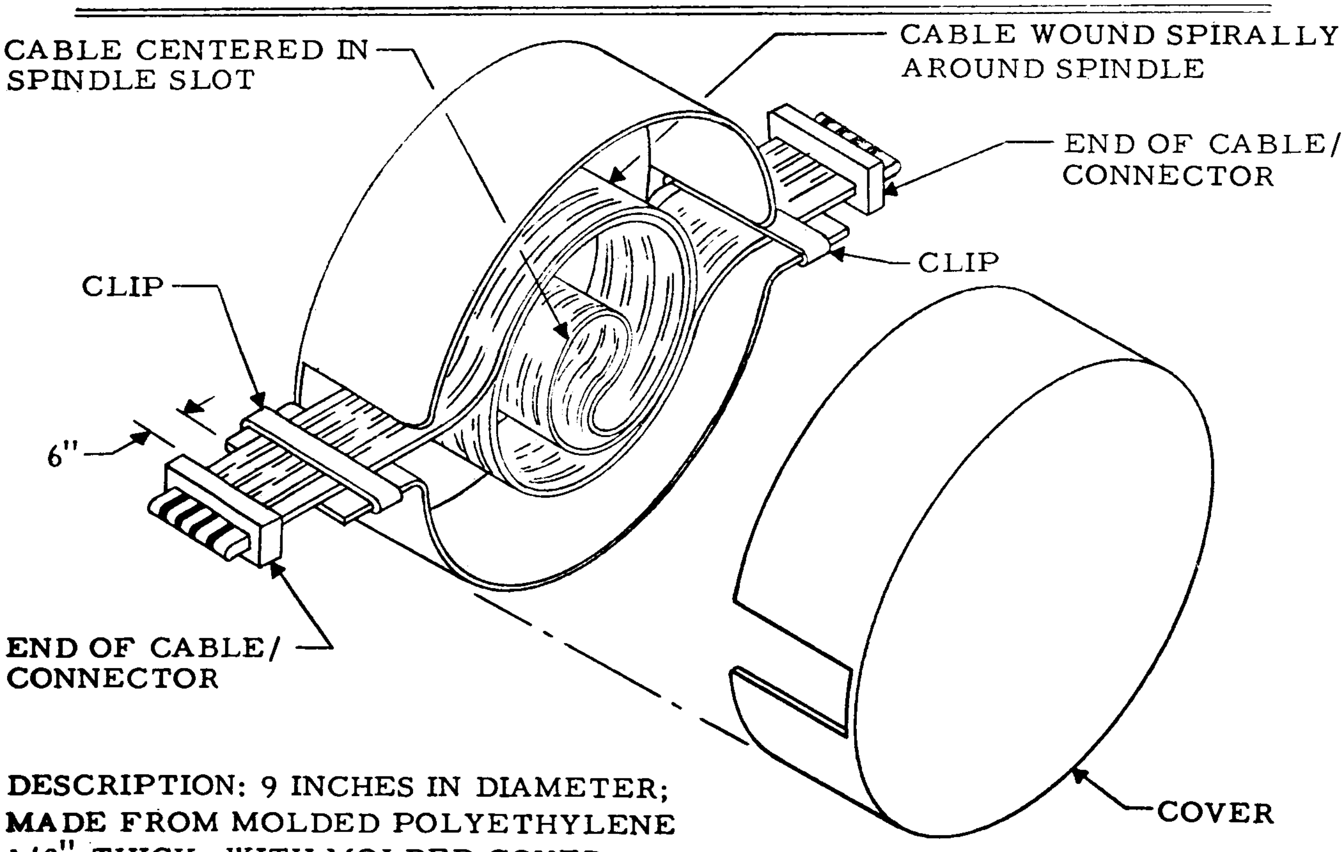


FIGURE 11-2 CONDUCTOR PROTECTING CLIP



DESCRIPTION: 9 INCHES IN DIAMETER; MADE FROM MOLDED POLYETHYLENE 1/8" THICK, WITH MOLDED COVER.

FIGURE 11-3 FCC HANDLING DEVICE

SECTION 12
HARNESS INSTALLATION

12.1 GENERAL

This section establishes the installation criteria that pertains to flat-conductor cable interconnecting harnesses. The intended application of Type VIII harnesses is for general use in areas outside the crew compartment.

12.2 PROCESS CONTROL REQUIREMENTS

Prior to installation of the completed harness assembly, verify that the harness has satisfactorily complied with all applicable processes, controls, and requirements of this document and applicable engineering design drawings. Assure that the harness has successfully passed functional testing and has been cleaned in accordance with Section 10 of this document. Special care shall be taken to assure that the harness packaging is free of physical or environmental damage, and identified in accordance with Section 9 of this document. Verify that the harness assembly is adequately protected from physical damage or contamination at all times, during and after installation, by application of temporary protective outer coverings. Before routing the harness assembly, verify that the area is ready for the harness, and that all sharp edges, protrusions, or structural members are covered with protective material as specified in the following paragraphs.

12.2.1 SAFETY

The application of safety measures and the required scope of compliance shall be determined by the Safety Representative. Care shall be exercised during the performance of the installation requirements of this document. Good workmanship practices are essential to the safety of the personnel installing the finished product, and to the equipment in which the harness may be an integral part.

12.2.2 FACILITIES

All harnesses shall be unpackaged and installed in a clean area. The general working area shall be maintained in a clean and orderly condition

12.2.2 FACILITIES (Continued)

at all times. Only tools', fixtures, test equipment, etc., which are required to perform the task shall be allowed in the area.

12.3 HARNESS PROTECTION

Whère harnesses pass near sharp or abrasive surfaces and may come in contact with such surfaces due to stresses during handling or flight, the harness shall be suitably protected to avoid any damage. The following paragraphs establish criteria for determining harness protection requirements, and provide techniques for eliminating potential damage conditions.

12.3.1 PROTECTIVE DEVICE REQUIREMENTS

A complete visual inspection shall be made of all surfaces coming into contact with harnesses to verify that no sharp or rough edges exist. Protective devices shall be installed to provide permanent harness protection from abrasion or other damage. Protection shall be installed where harnesses are routed across protruding or sharp edges of structures; through or across unprotected holes or cutouts; wnere cables can contact protruding rivets or other fasteners; and at any location where the danger of chafing the harness exists. Particular attention shall be given to harness slack in this respect.

12.3.2 CHAFING

Harnesses must be protected against damage that may result from rubbing against a surface or edge, or against any other object. Locations of possible abrasion damage (chafing) to the harnesses are as follows:

a. Where a harness passes around a corner of a shelf, bracket, equipment or structure.

b. Where a harness passes through a hole, and a clamp or grommet along is not adequate.

c. Where a harness is exposed to excessive contact by personnel or equipment.

d. Where harnesses pass near sharp edges of bolts, nuts, or rivets.

12.3.3 HARNESSES ON OR NEAR MOVING PARTS

Harnesses that are attached to assemblies where relative movement occurs, or near rotating parts, shall be installed and protected in such a manner as to prevent damage caused by movement. This deterioration includes abrasion

12.3.3 HARNESSES ON OR NEAR MOVING PARTS (Continued)

caused by one harness rubbing against another or by twisting and bending. Harnesses should be rerouted or protective devices shall be installed to provide permanent protection from abrasion and/or other damage.

12.3.4 PROTECTIVE GROMMETS

Where harnesses are routed over, or may contact any protrusions or sharp edges, protection of the harnesses will be provided by covering the protrusion or sharp edge with Teflon cushion or equivalent material. Where harnesses are routed over or through structural members that have Teflon caterpillar-type grommets, rigid grommets, or any protrusions and sharp edges, the harness should be supported by clamping to prevent the possibility of chafing. Figures 1 and 2 illustrate typical installations where grommet protection would be applied. When necessary to trim grommets to obtain proper fit, the gap after installation shall not exceed 1/10th inch. The angle of the cut shall be 45 degrees to the axis of the wire harness.

12.3.5 PROTECTIVE CLAMPING

Approved clamps shall be used to maintain the separation between any surface and the harness assembly. Harnesses shall be prevented from moving inside the clamp by selecting the proper clamp size and installing it with adequate tightness (see Section 13, "Support and Clamping"). Clamps used to support and separate harnesses from adjacent surfaces shall be attached to structure for support whenever possible. If supporting structure is not available, the clamps may be attached to lines carrying inert fluids such as water, helium, or nitrogen. (For lines carrying flammable fluids, see paragraph 12.4.2.) If the clamps are attached to the lines carrying inert fluids, the clamps shall be located close to those clamps which support the line itself. Cables shall not depend on insulating tubing to maintain a separation from any adjacent surface; except that insulating tubing shall enclose the cables when they lie on the inner surface of metallic conduit.

12.4 HARNESS INSTALLATION

Where possible, all harnesses shall be installed in the form of quickly removable and replaceable harnesses, attachable to and detachable from the the adjacent harnesses, regardless of function, location, or form of electrical

connection. All harnesses shall be installed so that installation or removal of equipment is permitted. Harnesses shall not be pulled to facilitate installation, nor to secure additional slack. Any visible evidence of damage to the harness is cause for rejection.

12.4.1 ROUTING

All flat-conductor cable harnesses shall be routed to avoid abrasion, cutting, or piercing of the outer insulation by contact with rough surfaces, sharp edges, or shockmounted equipment. Harness assemblies clamped to the structure shall be routed as directly as possible (insofar as practical harness assemblies shall be mounted parallel and/or perpendicular) and shall be protected along traffic lanes and near entrance areas where the harness is susceptible to use as handholds, steps, or other misuse. Harnesses may contact other harnesses provided they are suitably attached and routed to:

a. Provide accessibility for inspection and maintenance.
b. Prevent harness deterioration from high temperature or cold temperature extremes.
c. Minimize possibility of damage.
d. Minimize the need for protective material.

12.4.2 ROUTING NEAR FLAMMABLE FLUID LINES

Cables and cable bundles should be separated and supported away from lines containing flammable liquids, gases and oxygen, and associated equipment. Cables and cable bundles shall not normally be attached to lines and equipment containing flammable liquid gases, unless flammable lines and equipment require electrical connections. When clearance is less than 2 inches, separation shall be maintained by attaching a cable clamp to a fitting on the equipment or a clamp on the line, and no less than 1/2 inch separation shall be maintained. Reference Figure 3.

12.4.3 ROUTING NEAR NON-FLAMMABLE FLUID LINES

Where necessary due to structural characteristics, harness assemblies may be clamped to a non-flammable fluid line for separation. Installations shall be separated from non-flammable fluid lines by a minimum of 1/2 inch. Reference Figure 3.

12.4.4 IMPROPER CONNECTIONS

Where similar connectors arė used in adjacent locations, harnesses should be so routed and supported that improper connections cannot be made. When this requirement cannot be accomplished by routing, special markings or identification shall be provided to preclude improper connections.

12.4.5 DIRECTION OF BREAKOUTS

When breakouts of harnesses are made at a support clamp, they will, where possible, be made in a direction away from the clamp-cushion wedge or clamp-mounting screw. If the harness must break out in both directions, care shall be taken to ensure that the harness covering will not be damaged by the metallic portions of the clamp.

12.4.6 SLACK

Slack in harnesses between clamp installations shall be provided to avoid strain on cables in the harness or connections. Slack shall not be so great that the harness, under its own weight, or under acceleration or vibration loads, contacts sharp or rough objects that might damage the harness. Movement of the harness by hand shall not cause the harness to touch any adjacent surface. Movement by hand is defined as applying sufficient forces to move the harness without visibly distorting or moving the mounting clamps, or causing the harness to slide within the clamps. A 1/4 inch distance shall be maintained between the harness and any adjoining structure. Slack shall be minimized in order to achieve a neat and orderly appearance of the installation, but sufficient slack shall be provided for the following purposes:

a. To permit ease of maintenance and one or two reterminations, except where space limitation exist. In such cases, slack may be eliminated, providing no strain is placed on the cable termination.
b. To permit free movement of shock-and-vibration mounted equipment.
c. To prevent mechanical strain on the cable, cable supports, and cable junctions.

12.4.7 EXCESS LENGTH

Harnesses shall not be routed solely for the purpose of removing excess length. All excess harness shall be distributed throughout the total harness length, but shall not exceed the slack requirements between supports as specified in paragraph 12.4.6.

12.5 INSPECTION REQUIREMENTS FOR HARNESS INSTALLATION

Harness installation integrity shall be in compliance with all provisions of this document. Particular care shall be exercised to ensure such compliance prior to closeout of areas or where subsequent installations make inspection difficult.

CAUTION: Any inspections performed to verify integrity of installation shall be accomplished by visual examination where possible. Handling or movement of harnesses shall be minimized to that necessary to verify compliance. Due care must be exercised to avoid possible damage to a critical installation.

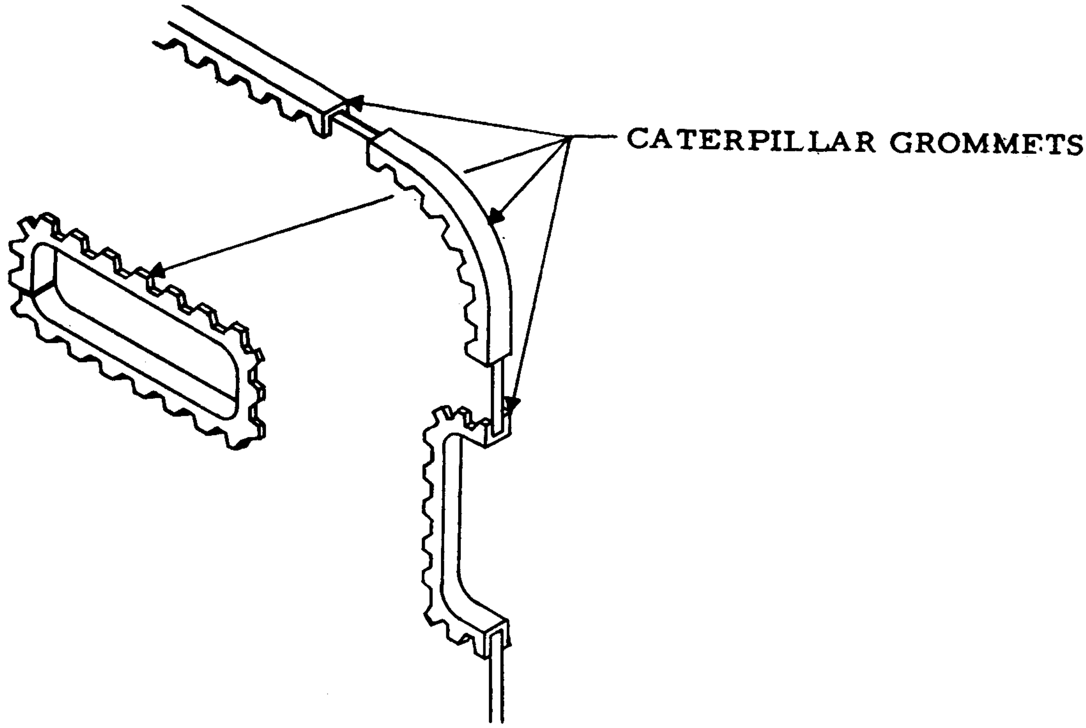


FIGURE 12-1 INSTALLATION OF CATERPILLAR GROMMETS

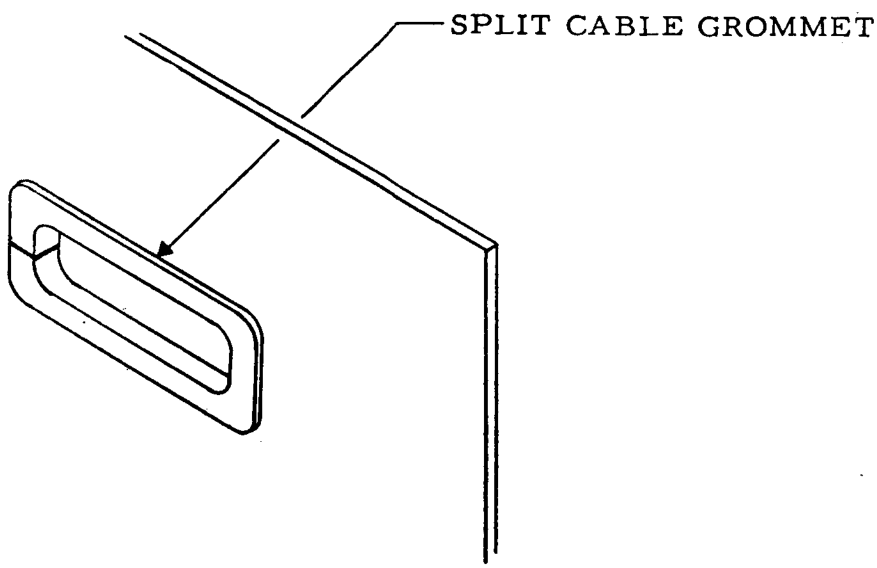


FIGURE 12-2 INSTALLATION OF SPLIT CABLE GROMMETS

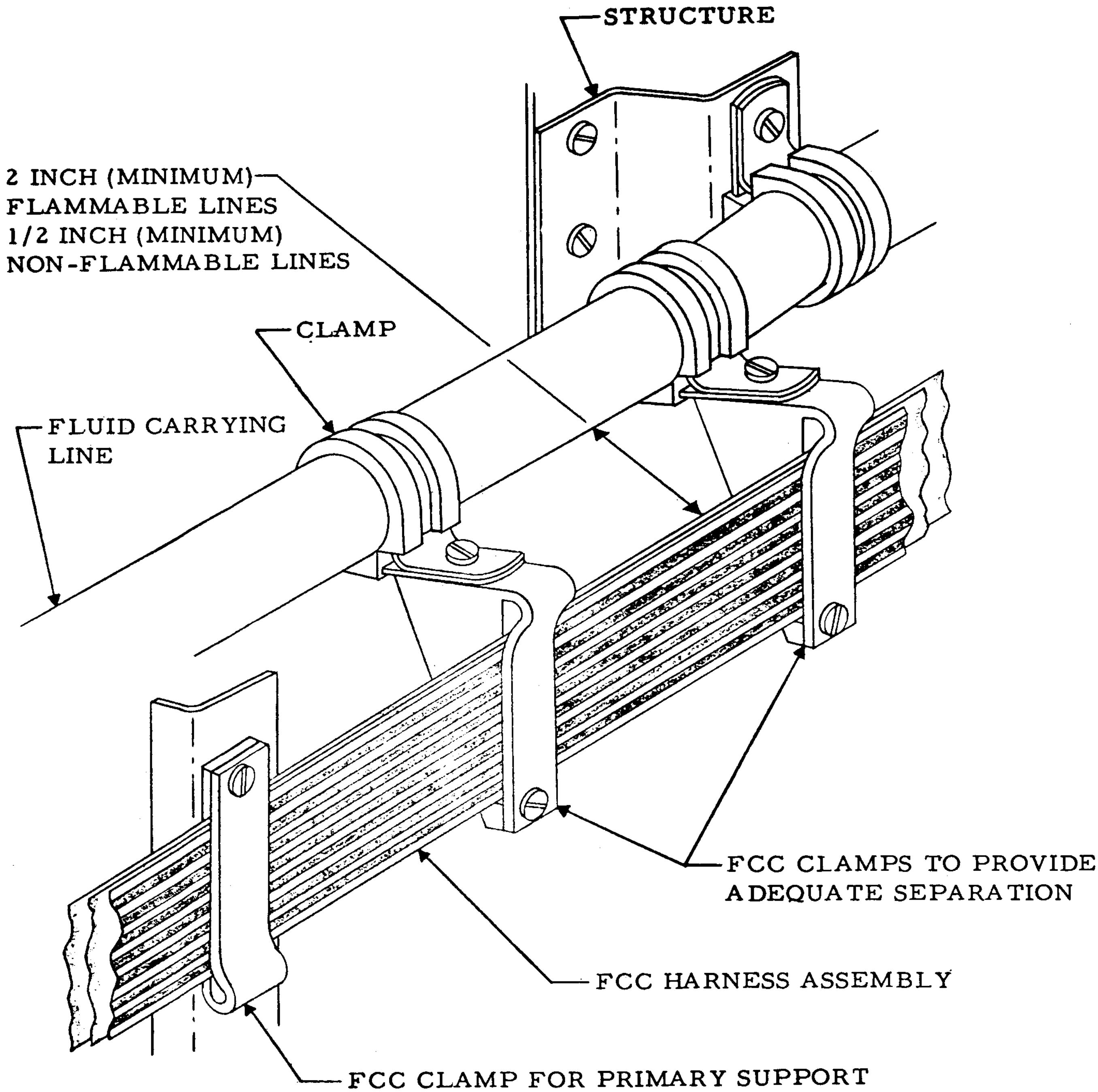


FIGURE 12-3 SEPARATION OF FCC HARNESSES FROM FLUID LINES

SECTION 13
SUPPORT AND CLAMPING

13.1 GENERAL

The primary purpose of the flat-conductor cable clamp is to secure and support the cable harnesses. These clamps are also utilized to reduce or eliminate vibration, to maintain clearance, and to relieve strain on cable terminating devices, shock/vibration mounts and other equipment. This section contains criteria relative to proper clamping techniques.

13.2 REQUIREMENTS

The standards, specifications, and engineering drawings that apply to installation of FCC harnesses shall include the clamping requirements for proper harness support. Installation of the supports and clamps for FCC is governed by the number of bundles, the distance between bundles, and the branches of each bundle. Cables are to be supported as required by engineering drawings, but the following criteria shall be considered during the installation process:

a. Prevention of chafing and migration within the support clamp.
b. Provision of clearance when harnesses are routed through or adjacent to bulkheads or structural members.
c. Maintenance of proper grouping during routing.
d. Prevention of mechanical strain that would break cables or connections.
e. Prevention of excessive movement under vibration.
f. Free movement of shock/vibration-mounted equipment.
g. Prevention of interference between harnesses and other equipment.

13.2.1 TEMPORARY SUPPORT PROVISIONS

All harnesses shall be adequately supported during installation to prevent damage due to excessive bending, kinking, or strain. Such supports shall be of a type which will not cause cold flow of the cable insulation. A simple hook, as illustrated in Figure 2, is sufficient for temporarily holding cables in place, and to allow additions or removal of cables without losing the position of the others. Regardless of the method selected, the support device must be capable of maintaining the harness(es) without

13.2.1 TEMPORARY SUPPORT PROVISIONS (Continued)

damage to the harness or adjacent structure or equipment.

13.3 CLAMPING DEVICES

In the fabrication and installation of harnesses, cushion-type clamps or non-cushion type clamps may be used for harness support. Clamping devices shall be of suitable size and type to hold the cables firmly without damage after fastening and without changing the shape of the bundle.

13.3.1 CLAMP SIZE SELECTION

Harnesses shall be supported by clamps as specified on the applicable installation drawing. To insure proper fit, it is recommended that provisions be made to allow deviation of clamp sizes larger or smaller that specified on the installation drawing. High temperature (200°C) cushioned, metal non-cushioned, or metal-cushioned, double grip clamps as illustrated in Figure 1, may be used on flat-conductor harnesses. In addition, the following criteria shall be used in selecting clamp sizes:

a. The size of the clamp shall permit the mounting tabs of the clamping device to be secured without deforming the cable harness.

b. Washers or other spacer devices shall not be installed on clamp mounting devices to obtain proper fit.

c. Deformation of the clamp or clamp cushion material shall be cause for rejection.

d. Clamps shall be of sufficient size that the harness is held firmly without the need of wrapped sleeving or tape, or the use of filler materials.

e. Clamp size shall be adequate to hold the harness securely in position without being pinched or damaged.

f. Clamping device shall have sufficient grip to prevent sliding of the harness inside the clamp after securing.

13.3.2 CABLE HARNESS INSTALLATION

Whenever a clamp is installed to support a harness, the entire harness must be contained within the clamp. The insulation material shall not be wedged between the mounting tabs of the clamp.

13.4 CLAMP AND SUPPORT INSTALLATION

Harness assemblies supported by clamps shall be secured to the vehicle structure with support sections as illustrated in Figure 3. The modular hole patterns on the clamp mounting surfaces permit the acceptance of the modular-width clamps selected. The various support sections may be bonded, riveted, or bolted to existing structure. When harnesses are routed over or through structural members that have grommets, or any other protrusions and sharp edges, the harness shall be supported by clamping to prevent the possibility of chafing.

13.4.1 LOCATION

Normal harness runs shall be supported by clamps at intervals of not more than fifteen inches. The location of clamp devices shall ensure harness support against vibration, chafing, or general harness damage, and shall be sufficient to maintain the desired harness installation configuration. The following criteria shall be used as a basis for nominal clamp spacing:

a. The distance between the first clamp and the back of the connector shall be no greater than 15 inches.

b. Harnesses shall be supported at intervals not to exceed 15 inches.

c. Where harnesses are routed through or over grommets, the harness shall be supported by clamping as close as practical to the grommet.

13.4.2 MOUNTING OF CLAMPS

Support clamps shall be firmly secured and installed at right angles to the harness to minimize the possibility of abrasion from edges of clamps. The installation of a typical high-temperature flat-conductor cable clamp is accomplished as follows:

a. The harness is aligned and positioned on the support.

b. The clamp is positioned on top of the harness.

c. The fasteners in each end of the clamp are aligned with the holes in the support.

d. Pressure is applied on the clamp until the spacers of the clamp come in contact with the support.

e. The fasteners are turned to secure the clamp to the support.

13.5 SUPPORT AND CLAMPING ACCEPTANCE CRITERIA

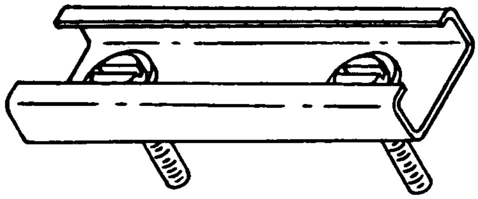
The installation of the supports and clamps for flat-conductor cable is governed by the number of bundles, the distance between bundles, and the branches of each bundle. Since the type of clamps and the exact method of installation will vary depending upon the particular application, a general inspection plan is presented. The installation of clamps and supports should consist of the following general inspection points and areas of concern:

a. Area of clamp or support attachment should be clean and free of all contamination and oxidation.

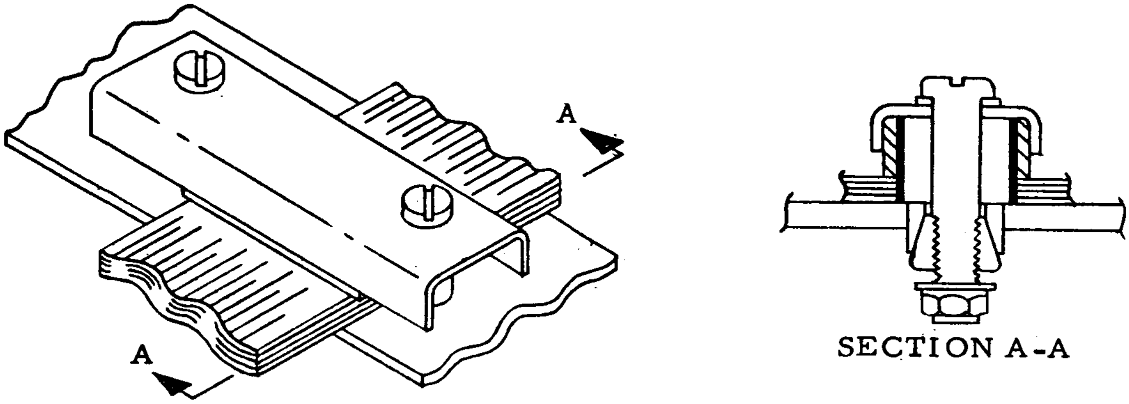
b. The clamps must be aligned properly to accommodate the number of cable bundles required.

c. The clamps and supports should be placed at appropriate intervals to prevent excessive cable slack. Support should be placed at least every 15 inches.

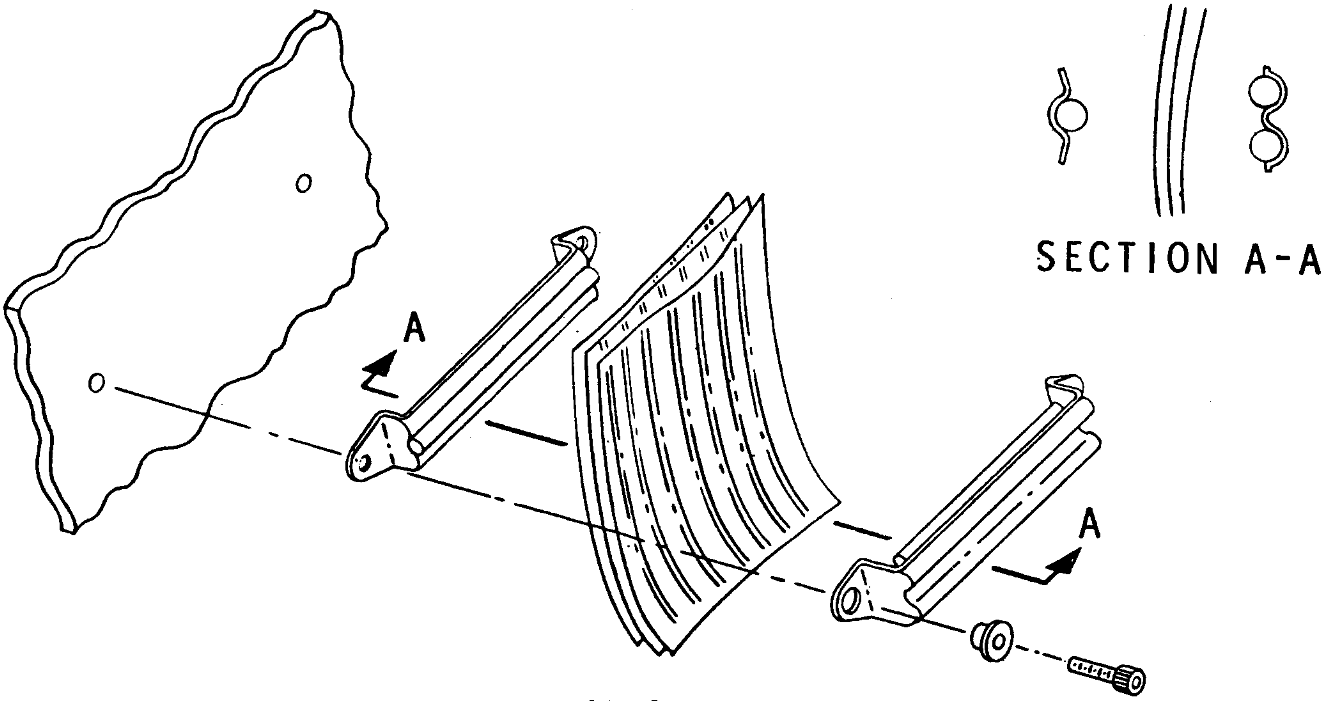
d. Clamps should provide a snug grip on the cable bundles to prevent chafing and travel of the cable bundle.



A. METAL NON-CUSHIONED CLAMP



B. DOUBLE GRIP CLAMP



C. CUSHIONED CLAMP

FIGURE 13-1 HIGH TEMPERATURE CABLE CLAMPS

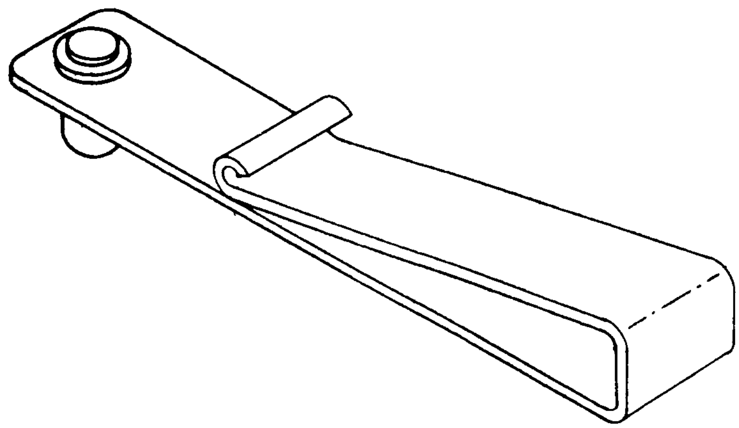


FIGURE 13-2 TEMPORARY FCC INSTALLATION SUPPORT HOOK

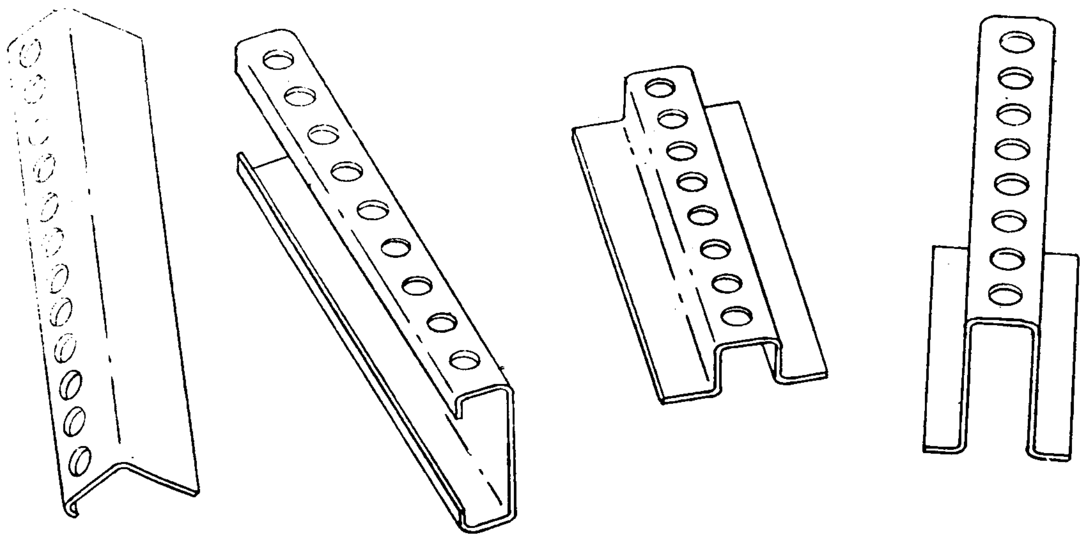


FIGURE 13-3 CLAMP SUPPORT SECTIONS

SECTION 14

CONNECTOR MATING

14.1 GENERAL

This section establishes the standard processes related to mating of premolded rectangular plugs and molded-on cylindrical plugs. The criteria contained in the following paragraphs shall apply to both type plugs, except where noted.

14.2 PROCESS CONTROL REQUIREMENTS

Immediately prior to mating, visually examine each plug to ensure that:

a. The insert faces are clean and free of chips, dirt, mold flash, or any foreign materials that would cause damage, or that would prevent the plug from easily entering the receptacle.

b. The plug seals are clean, free of damage, and properly cemented in the plug face.

c. The sockets in the receptacle are not abnormally recessed or extended.

d. There are no nicks, fractures, or imperfections in the connector housing.

e. The conductor plating is free of flaking, porosity, roughness, or non-adhesion.

f. Plugs and receptacles are properly marked so that "P" and "J" match, and key configurations are compatible.

14.2.1 CONNECTOR PROTECTION

All connectors shall have protective caps installed throughout all stages of fabrication and installation, except when mated. The caps shall provide both environmental and physical protection.

NOTE: Protective caps on the connectors may be removed during the visual examination, but must be re-installed and remain in place until the connectors are ready to be coupled.

14.2.2 PRECAUTIONARY PROCEDURES

Caution shall be exercised when mating connectors to ensure that damage does not occur to plug or receptacle. Under no conditions shall connectors be

14.2.2 PRECAUTIONARY PROCEDURES (Continued)

subjected to undue manual force during the installation process. In addition, the following precautionary procedures shall be adhered to:

a. There should be adequate cable length for bundle flexing during connector coupling and uncoupling.

b. Cable bundles shall not be pulled to obtain the required length needed to complete the mating of connectors.

14.3 CONNECTOR MATING

Mating procedures for the two types of connectors are covered in the following paragraphs; (1) the rectangular pre-molded type which utilizes plug retainer clips; and (2) the molded-on cylindrical type which secures with a threaded coupling ring.

14.3.1 RECTANGULAR TYPE CONNECTOR INSTALLATION

When rectangular type plugs and receptacles are to be mated, align the mating keys on the plug with the key-ways on the receptacle, and engage by inserting plug into the receptacle until mated. Do not rock plug side-to-side during mating or unmating. After mating, secure the plug to the receptacle using the plug retainer clips located on the receptacle, and safety wire as described in paragraph 14.4. Mated connector is illustrated in Figure 1.

14.3.2 CYLINDRICAL TYPE CONNECTOR INSTALLATION

The cylindrical type connector employs key-slots in the receptacle and corresponding mating keys in the plug to ensure proper plug to receptacle orientation prior to engagement of the threaded coupling ring. Engagement is performed by aligning keys with keyways and inserting plug into the receptacle. Do not rock plug side-to-side during mating or unmating. Following mating, the connector shall be secured by tightening the threaded coupling ring as far as travel permits, by hand to permit proper alignment and prevent damage to threads. The connector shall be safety wired as described in paragraph 14.4, after securing. Mated connector is illustrated in Figure 2.

14.4 SAFETY WIRING

Safety wire shall be applied so that the connector will not loosen. The safety wire shall be installed with a double twist method and shall have 6-14 twists per lineal inch. The tag ends of the wire shall have 3 to 6 twists and

14.4 SAFETY WIRING (Continued)

shall be neatly trimmed to a length of approximately 1/2-inch. The tag ends shall be bent back against the connector to avoid snagging or scratching any object. The final installation of safety wire shall be correctly positioned with sufficient tension so that the wire cannot be moved or slid in any direction which could permit loosening. The wire shall have the shortest possible length. Acceptable methods for installing safety wire on both rectangular and cylindrical connectors are shown in Figures 1 and 2.

14.5 QUALITY CONTROL SEALING

Quality control seals shall be installed after the connector has been mated. Seals will be installed in such a manner that the retainer clips or threaded coupling ring, as applicable, cannot be disengaged without breaking the seal. The seals and the environment in which they are used shall be compatible. Connectors with broken seals shall be subjected to a thorough reinspection to assure connector integrity, and then resealed.

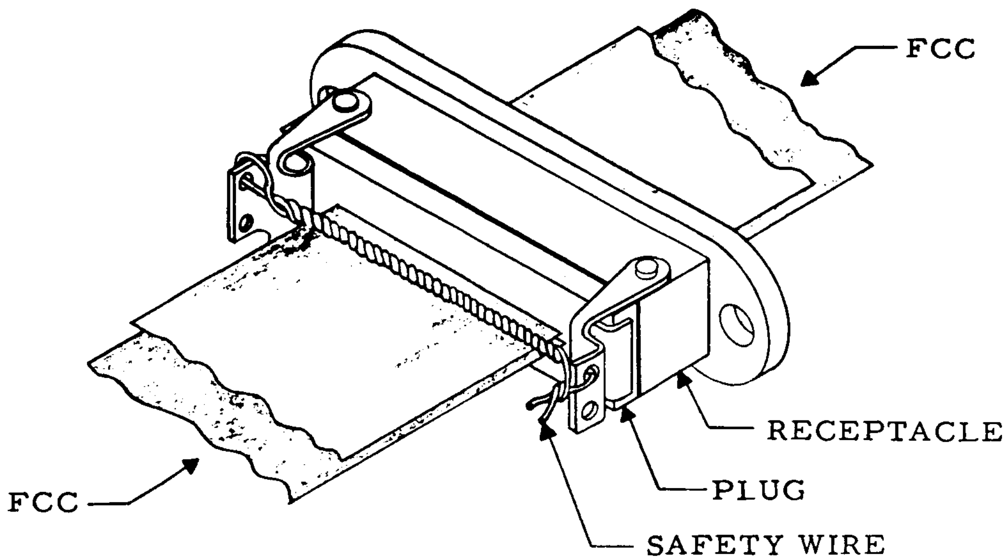


FIGURE 14-1 MATING AND SAFETY WIRING OF RECTANGULAR CONNECTORS

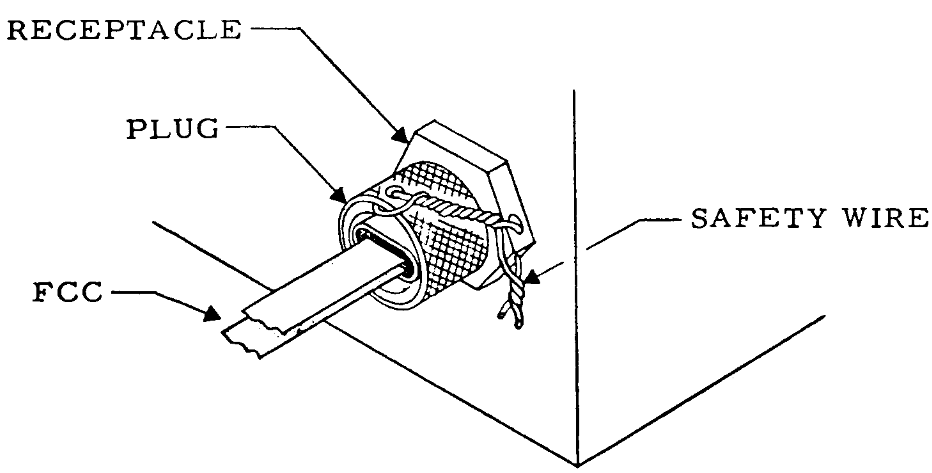


FIGURE 14-2 MATING AND SAFETY WIRING OF CYLINDRICAL CONNECTORS

SECTION 15

Test

15.1 GENERAL

This section establishes the requirements for performing continuity, insulation resistance, and dielectric withstanding voltage tests of electrical harness assemblies. Acceptable harness continuity will be assured by determining that the cable conductor resistance is less than the specified maximum value. Acceptable insulation resistance will be assured by determining that the cable insulation resistance is higher than the specified minimum value. Performance of the dielectric withstanding voltage test will assure that the cable insulation material and connector terminations have not been degraded during previous fabrication and handling operations. The continuity and insulation resistance tests may be performed, at the option of the harness fabricator, whenever it is deemed prudent to assure the status of electrical integrity prior to performing a manufacturing process, such as potting of connectors. The performance of these interim tests does not preclude performance of the mandatory final post-fabrication tests.

15.2 SAFETY REQUIREMENTS

Care shall be exercised during dielectric withstanding voltage and insulation resistance tests, which are performed at voltages hazardous to operating personnel. All test equipment used during the tests shall be thoroughly grounded and shall incorporate protective devices to guard personnel against electric shock. Personnel shall be kept away from output terminals of any test equipment, test cables, and harnesses while the tests are being performed.

15.3 TEST PREPARATION REQUIREMENTS

Preliminary preparation prior to electrical tests shall consist of verification that the harness assembly has satisfactorily completed the scheduled fabrication processes and is ready for test. Verify that all required test equipment is ready and is of the proper type, and has current

15.3 <u>TEST PREPARATION REQUIREMENTS</u> (Continued)

calibration certification. All personnel involved in the testing of harness assemblies shall be properly instructed and adequately trained to operate the test equipment per the test procedure.

15.3.1 SPECIAL PRECAUTIONS

Receptacles shall be mated to plug under test prior to attaching test leads. The type and size of mating test receptacle must match the connector undergoing test. Prior to connector mating and following connector demating verify that connectors are free of damage. Mating or demating of individual connectors must be done carefully to prevent damage to the connector shell and the connector contacts. A connector shall <u>never</u> be demated while a test voltage is being applied to the connector. Always verify that connector protective covers are installed or replaced on unmated connectors following testing.

WARNING: Under no circumstances shall insulation be probed with test lead probes or clips nor shall probes or clips be permitted to touch or be attached to the connector contacts.

15.3.2 PRE-POTTING PRE-TEST VERIFICATION

Prior to pre-potting electrical test, verify that all connectors are free of contamination. Examine connector for damage, recessed or bent contacts, and other damage that may occur during handling and previous processes.

15.3.3 HARNESS POST-FABRICATION PRE-TEST VERIFICATION

Prior to the post-fabrication test which follows completion of harness fabrication, assure that the completed harness assembly has complied with all applicable drawings, design criteria, fabrication requirements, and workmanship requirements, e.g., overall dimensions, harness identification, and handling damage (connector bent contacts and damaged, missing, or improper seals).

15.3.4 HARNESS POST-INSTALLATION PRE-TEST VERIFICATION

Prior to the post-installation tests verify that all connectors remain demated and that the harness assembly has been installed correctly and has protection from chafing, proper clamping and marking. Check all connectors

15.3.4 HARNESS POST-INSTALLATION PRE-TEST VERIFICATION (Continued)

for obvious handling damage prior to test.

15.4 HARNESS ASSEMBLY CONTINUITY TEST REQUIREMENTS

Each harness assembly shall be tested for point to point electrical continuity in accordance with the applicable wiring diagrams or engineering documentation. The circuit resistance shall be a maximum allowable of two (2) ohms, and the test voltage shall not exceed 50 Vdc. Any circuit having a resistance value greater than two (2) ohms, excluding the resistance in the test equipment and adapter cables, will be considered unacceptable.

15.5 HARNESS ASSEMBLY DIELECTRIC WITHSTANDING VOLTAGE (DWV) REQUIREMENTS

Whenever the dielectric withstanding voltage test is performed it shall be performed after the continuity test and be followed by the insulation resistance test. Since this (DWV) test is generally recognized as potentially accumulatively destructive to insulation, the test is performed once on the harness assembly, at the completion of harness fabrication. The harness assembly shall be capable of withstanding the application of 1000 volts (minimum) RMS, 60 CPS, or 1500 volts dc power for one minute maximum. Leakage current shall not exceed 0.5 millampheres. An appropriate current measuring device, capable of indicating leakage current of 0.5 millampheres or greater, and breakdown due to a sustained arc, shall be used during performance of this test. The voltage shall be applied at a rate of 500 volts per second, and snall be maintained for a maximum of one minute between:

a. Each conductor and all other connector contact terminated conductors in the same harness assembly.

b. Each conductor and each connector shell. (Not applicable to non-metallic shells.)

c. Each spare connector contact and all other contacts (wired or spare) and connector shell. (Not applicable to non-metallic shells.)

The test voltage shall be maintained for sufficient time, not exceeding one minute, to assure that the leakage current has reached a steady state condition. Test methods shall comply with method 301 of MIL-STD-202.

15.6 HARNESS ASSEMBLY INSULATION RESISTANCE TEST REQUIREMENTS

A test potential of 500 volts dc, plus or minus 25 volts dc, shall be applied for a minimum dwell time of 60 seconds. The measured insulation resistance shall be greater than 100 megohms.

15.6.1 POST-FABRICATION TEST

Harness assembly insulation resistance shall be measured between:

a. Each conductor and all other connector contact terminated conductors in the same harness assembly.

b. Each conductor and each connector shell. (Not applicable to non-metallic shells.)

c. Each spare connector contact and all other contacts (wired or spare) and connector shell. (Not applicable to non-metallic shells.)

15.6.3 POST-INSTALLATION TEST

Harness assembly insulation resistance shall be measured between:

a. Each conductor and all other connector contact terminated conductors in the same harness assembly.

b. Each conductor and each connector shell. (Not applicable to non-metallic shells.)

c. Space vehicle/payload structure and each conductor, and connector shell. (Not applicable to non-metallic shells.)

15.7 TEST OPERATIONS

Test operations shall assure that the test requirements are fulfilled.

15.7.1 POST-FABRICATION TESTING TECHNIQUE

Automatic or manual test equipment may be employed for post-fabrication continuity, dielectric withstanding voltage, and insulation resistance testing. When more complex harness configurations are involved, such as a harness having more than a nominal number of connectors or having a design such that a master connector, or two, is not evident, the automatic test equipment is highly desirable. Test adapter harnesses connected to each connector or junction device of the harness under test, and terminated in the automatic test equipment, will allow total test of all the parameters stated above as test requirements. An automatic test program can be prepared as a universal program, with resulting test anomalies being judged

15.7.1 POST-FABRICATION TESTING TECHNIQUE (Continued)

as either prescribed design or nonconformances. Automatic equipment with a universal program affords minimum test preparation and maximum repeatability. The test program may be further reduced during the dielectric withstanding voltage test and the insulation resistance test by "commoning" within the test equipment all conductors, connector shells (not applicable to non-metallic shells), that one conductor to be tested, and applying the test voltage between the conductor and the "commoned" conductors, etc. Evidenced anomalies will necessitate isolation of fault, while acceptable results simplify testing.

15.7.2 POST-INSTALLATION TESTING TECHNIQUE

Automatic or manual test equipment may also be employed for post-installation continuity and insulation resistance testing, as employed in the post-fabrication testing. However, due to the restrictions imposed by more complex space vehicle/payload structures, the accessability of installed harness connectors, weight limitations, etc., automatic equipment may not be advised. Manual continuity testing is achieved by identifying the appropriate harness assembly connectors and measuring the resistance between the terminal ends of each conductor; long test leads are generally required and may require consideration in measuring circuit resistance. Manual insulation resistance testing is accomplished by identifying those harness assembly connectors in which one end of each harness conductor is terminated and applying the test voltage between each conductor terminated in the connector under test and the balance of the conductors, connector shells (not applicable to non-metallic shells), and space vehicle/payload structure"commoned" via a test unit. To afford test between each conductor and all the connector shells during manual testing, all of the harness assembly connector shells not otherwise mounted to structure should be electrically connected to the space vehicle/payload structure, thus being "commoned" with the structure for test purposes (not applicable to non-metallic shells). This electrical connection is best achieved, with minimum chance of connector damage, by employing a special single conductor jumper equipped with a clip at one end for attachment to a structure "ground" stud and a soft metal nominal size coiled spring, looped end-to-end, at the other end of the jumper. The looped spring can be slipped over the connector shell and retain its position of electrical contact with the connector shell.

SECTION 16

POST INSTALLATION VERIFICATION

16.1 GENERAL

A post installation review shall be performed, upon the completion of installation of all harnesses and other manufacturing operations performed in the vicinity of harness installations. This review may be completed in appropriate increments if the installation areas are conveniently defined and completion of all manufacturing operations is so segmented. This section is provided as a basic guideline for performance of the post installation verification review and is intended for use in development of a complete and comprehensive installation review procedure.

16.2 PURPOSE

The objectives of the post installation verification review are (1) assessment of the installed wire harness routing, clamping, connector mating, and general lay to assure that the previously accepted installation of each harness has not been compromised by subsequent near-proximity manufacturing operations, harness installations, hardware modifications, etc; (2) general assessment of each installed harness, with emphasis on potentially susceptible areas, for damage or potential compromise of harness integrity; and (3) identification and formulation of design changes which (2) remove or reduce the potential of damage to networks harnesses during subsequent testing, handling, and mission performance, (b) provide improvement of crew and operator safety, and (c) improve the overall quality and reliability of the electrical networks.

16.3 POST INSTALLATION VERIFICATION

When it can be ascertained that all manufacturing operations have been completed within a distinct portion of an end assembly, a post installation verification review of all electrical networks harnesses comprising the completed area shall be performed. Special attention shall be given in

16.3 POST INSTALLATION VERIFICATION (Continued)

designating such areas to assure that such areas are not influenced by subsequent manufacturing operations, in adjacent areas, which would cause invalidation of an area verification review. Those harness installations which are enclosed in covered troughs or otherwise hidden from view by subsequent manufacturing operations shall be subjected to post installation verification review immediately prior to covering, thus precluding disassembly of hardware for performance of this review. However, special attention should be given to subsequent near-proximity manufacturing operations to assure that hidden damage is not incurred.

16.3.1 FIRST ITEM REVIEW

The post installation verification review of the first production item shall be attended by the responsible design engineering group so that resolution of problem areas (potential or real) which can be corrected by design change can be expedited. Possible design considerations may include re-routing or combining harness segments, adding separators or clamps, revising harness lengths, etc., and shall be freely advanced to assure that the production item displays clean, orderly appearing harness installations of the highest quality. The participation of the design engineering group in this first quality review will also allow a cross fertilization of problems recognized by the participating quality assurance group.

16.3.2 QUALITY VERIFICATION CRITERIA

The following checklist is provided as guidelines to inspection personnel. These guidelines are not to be construed as a complete list; inspecting personnel and persons compiling the inspection procedure are expected to employ their experience and knowledge of good harness installations practices and their initiative to insure the highest standard of quality:

a. Harness fabrication quality has not been degraded by assembly/ installation operations or other activities.

   1. Identification
   2. Corrosion
   3. Deformed or broken connectors

16.3.2 QUALITY VERIFICATION CRITERIA (Continued)

4. Fractured potting
5. Cleanliness (harnesses free from foreign matter)
6. Ruptured sleeving or sheathing
7. Disturbed shielding

b. Harness installation has not be degraded.

1. Support and clamping
2. Protective wrapping, convolute, sheath, etc.
3. Bend radius
4. Slack
5. Correct clamp (cushion not damaged)
6. Capping and stowage
7. Lacing and tying
8. Grounding/bonding
9. Spacing of harnesses

c. Connector mating has been properly performed or connectors stowed.

1. All harness connectors have been properly mated or stowed.
2. Torquing has been accomplished, as specified.
3. Safety wires are as prescribed, none broken, and no sharp strands.
4. Quality seals are in place and have not been broken.

ENERGY PULSE BONDING

By G. C. Smith
Bendix Corp.

A NEW METHOD OF JOINING FLAT CABLES

ENERGY PULSE BONDING

ABSTRACT

To eliminate many of the present termination problems a technique called Energy Pulse Bonding (EPB) has been developed. The process demonstrated the capability of (1) joining conductors without prior removal of insulations, (2) joining conductors without danger of brittle intermetallics, (3) increased joint temperature capability, (4) simultaneous formation of several bonds, (5) capability of higher joint density, and (6) a production oriented process. The following metals were successfully bonded in the solid state: copper, beryllium copper, phosphor bronze, aluminum, brass, and Kovar.

INTRODUCTION

Over the last decade the advancement of usage and capability of flat cable, with both round and rectangular conductors, has brought along with it new termination problems. These problems are encountered due to physical configurations, conductor densities, and the wide variety of insulations being used. It has also created new requirements in configurations for connecting devices and connector density capabilities.

The terminating problems of joining flat cable conductors to various devices such as connectors, printed circuit boards, other flat cable, individual round wire, etc. has been attacked with a variety of ingenious methods utilizing old and new techniques. Various soldering methods have been used extensively, but these are temperature limited and require removing the conductor insulations. Removal of flat cable insulations in itself requires special devices utilizing mechanical, thermal, or chemical techniques depending on the insulating material. Resistance welding is being widely employed, even with some processes capable of forming welds through the insulations but, like all welding operations, joining takes place through fusion which inherently results in a cast microstructure and forms alloys or brittle intermetallics at the joint interface between two dissimilar metals. It is additionally limited to formation of one joint at a time. Some very impressive crimping operations have been developed allowing terminations through conductor insulations and obtaining very respectable crimping rates. There are, however, two main limitations. One is the required conductor spacing and the other is the higher and more erratic contact resistance encountered, which will be greatly affected by temperature cycling and exposure to industrial gases.

Energy pulse bonding utilizes the old science of thermocompression bonding where the bond is formed through the mechanism of atomic diffusion. It two atomically clean mating surfaces are brought close enough together so that interatomic forces become effective, theoretically, a solid bond will form at the interface. Due to unbalanced interatomic forces at the free surfaces, surface atoms will form bonds across the interface in order to lower the surface energy. If the bonding time is long enough, the interface bond can also be formed by atomic diffusion mechanisms. There are three geometrically possible ways in which the atoms of a crystal can make diffusive movements.

1. By direct interchange of adjacent atoms or by simultaneous movement of atoms constituting a ring.

2. By the movement of interstitial atoms or through the formation of a crowdion within the crystal.

3. By the vacancy mechanism where if an atom obtains sufficient energy and there is a vacant site, it will jump from its present position to the vacant site.

Other aids to the formation of the bond come from grain boundary diffusion and surface diffusion at low temperatures, but it is believed that the bulk of the diffusion occurs from the diffusion in crystals at high temperatures.

Since all surfaces are not atomically clean and contain many asperity points, high deforming pressures are utilized to disperse surface contaminants and create larger contact areas. Thermal energy is used to aid in the diffusive bond mechanism.

The energy pulse bonding technique uses mechanical pressure and high temperature in the form of a controlled energy pulse (Fig. 1) where the amplitude and time duration are carefully controlled. The mechanical pressure, guided by the yield strength of the conductor material, causes microscopic plastic deformation of the surface asperities bringing more area into intimate contact, dispersing of surface contaminants and minimizing voids at the bond interface. With sufficient material deformation and short bonding time at low temperatures, voids and an interfacial bond line will be present (Fig. 2a) which may exhibit good tensile strength characteristics but poor peel strength. With proper bond pressures, a joint interface will not be detectable as shown in Figure 2b.

Another important bond parameter is temperature which aids in the migration of atoms across the bond interface forming a joint. The bond

temperature utilized in EPB is between 50 and 75 percent of the melting point for the conductor material, therefore eliminating the possibility of joint formation through fusion as occurs in welding. Here, crystallization and grain growth promotes a homogeneous bond interface between two like materials. The higher temperatures also aid in reducing the pressure at which plastic deformation of the asperity points will occur. A factor which may limit bond temperatures occurs in instances where the retention of cold-working or heat-treated properties may be desired.

Time, a third parameter, is dependent on bonding temperature, pressure, and ram characteristics. With higher temperatures and pressures, joint formation will occur at shorter times (seconds) where, at lower parameters, the required time is measured in minutes or hours. The third factor is the rate at which thermal energy is transferred from the bonding head to the work parts. This has been tremendously improved (Fig. 3) by the use of a dual ram over a single ram bonding system where heat is applied from two directions to the work part (Fig. 4).

Another factor to consider in EPB is required surface preparation and preservation. To obtain a successful bond it is necessary to make intimate contact between joining surfaces and the greater the contact area the better the chances for a successful bond. To aid in bond formation it is helpful to generate a smooth surface finish and remove oxides and films. However, an objective of this investigation is the forming of reliable bonds without the added cost of cleaning time and equipment. Therefore, all bonding has been done without employing special cleaning procedures. It has been found that with the higher pressures and temperatures, the surface cleanliness becomes less critical due to the increased atomic mobility, surface asperity deformation, and dispersion of surface contaminants. This is an important aspect when production bonding in industrial atmospheres is considered.

BONDING EQUIPMENT

Although the required bonding equipment is relatively simple, including a pneumatic press, bonding heads, and controller for temperature-pressure-time, there are certain factors to which special consideration must be given.

The energy pulse is applied to the work parts by continually heated thermal masses, one mounted in a pneumatic press and the other stationary (Fig. 4). These thermal masses, the bonding heads, are the heart of the system and must include design consideration for thermal mass, thermal

conductivity, thermal distribution, mechanical strength, and bond face geometry.

Presently, the rams are heated by a cartridge heater specially designed to provide even-heat to reduce thermal distribution across the ram face. The thermal conductivity of the ram material plays a dual role; one is the effect on thermal energy transfer from the ram to the work parts. However, because of the requirement for mechanical strength, a tradeoff is necessary between material thermal conductivity and yield strength. It has been found that with the dual ram system, the thermal conductivity is less critical and a material of higher yield strength can be selected to provide better bonding head life. The thermal mass is selected on the basis of specific heat and size of both the ram and parts to be bonded. This is to insure that the thermal drain per operation does not require waiting for the rams to recover the required bonding temperature.

The geometry of the bonding surface will depend on the parts to be bonded. For general bonding, a solid surface is used with a bonding width of approximately 0.075 inch (Fig. 5a). For other applications, protrusions on both rams (Fig. 5b) may be used to localize the pressure and temperature, or protrusions on one ram and grooves on the other (Fig. 5c) may be used to confine conductor spreading, especially with stranded wire conductors.

In selecting a bonding press, particular attention must be given to the alignment of the bonding heads to provide equal bond pressures at all bond points across the ram face. The pressure control system consists of regulating input pressure, approach pressure, and bond pressure. The input pressure along with piston design controls the force range capability of the system with approach pressure regulating the closing rate of the rams and, finally, the bond pressure controlling the desired actual force applied to the work parts forming a joint.

Through the use of commercially available temperature controllers, each ram is independently regulated to allow a variation of ram temperature combinations. The temperature range depends on desired versatility of the system. Bond, or dwell times, are electronically controlled and initiate from the application of the bond pressure. Again, dwell time is dependent on desired system versatility.

System size including press, pneumatics, and electronics is approximately 2 ft^2 by 5 ft high with an approximate weight of 600 pounds. The only necessary input requirements are a 100 psi air line and 115 volts power with

2000 watt capability for average size heads. Larger heads will, of course, require proportionally more power.

By providing automatic feed, loading and unloading devices with intelligent design considerations given to the foregoing factors, the process can be made semi or fully automatic and with process control of the bond parameters of temperature, pressure, and time will rapidly turn out reliable joints.

PROCESS INVESTIGATION

The bulk of the investigation has been in utilizing the knowledge that a bond can be formed between metals under certain conditions of temperature and pressure and determining its capabilities and applications, especially in the area of terminating flat cable. The actual bonding mechanism is also being further investigated to obtain a more complete understanding of the process.

The area under investigation is very broad and was reduced to include the following main interests:

1. Joining of various like metals.
2. Joining of dissimilar metals.
3. Effects of plating.
4. Effects of conductor geometry.
5. Effects of surface contaminants and insulations.
6. Effects of conductor densities.

To examine the capabilities of joining various like and dissimilar metals, a group was selected which is most prevalent in conductors use along with the more common platings. This list includes copper, beryllium copper, phosphor bronze, brass, Kovar, and aluminum, plus gold, silver, and nickel platings.

A common test sample configuration was selected for the evaluation using 0.010-inch material with 23 leads on 0.050-inch centers, 0.020-inch wide by 1.000-inch long. Samples of each material were chemically milled into the above-described sample configuration. Each sample was then bonded to like and dissimilar material samples over a range of bond parameters

including temperature, pressure, and time. Initially, time was held constant at some duration less than 10 seconds with temperature beginning at 50 percent of the material melting point with pressures approximately equal to its yield strength. The optimum bond parameters were then obtained by bonding test samples at variations of pressure and temperature and then performing tensile and peel tests on the bonded joint. The peel tests were made at an agle of 180 degrees to the joint interface. The types of bonds were then classified as:

1. No bond where parameters were insufficient for forming bonds.

2. Unsuccessful bond where joint failed.

3. Successful bond where joint did not fail.

4. Bond failure where parameters were excessive.

The classified joint was then plotted on a graph of temperature versus pressure and the area of successful bond noted (Fig. 6). The EPB joints were also compared against joints made by soldering, resistance welding, and crimping.

Other bond evaluation techniques included microsectioned samples, microhardness tests, microprobe analysis, contact resistance, and current-carrying capacity.

Microsections revealed joint voids, inclusions, interface line, and effects on materials crystalline structure. Microhardness measurements revealed formation or lack of formation of brittle intermetallics at the joint interface and microprobe analysis determined the extent of diffusion occurrence during a bonding operation. Electrical characteristics for the joint should include contact resistance equal to or less than that of the lead itself with current capacity equal to or greater than the lead. The electrical characteristics of joints formed by EPB were also compared with equivalent joints formed by soldering, resistance welding, and crimping.

In the bonding of flat cables, an evaluation program was used as described above utilizing commercially available cable and with the addition of one very important analytical process called Thermo-Gravimetric Analysis. In flat cable applications, an important objective was the formation of bonds without the necessity of prior insulation removal. This was accomplished through the combination of heat, to melt or vaporize the insulation, and ram face design to allow the displacement of the insulation. To evaluate temperature

requirements for insulation removal, a Thermo-Gravimetric Analysis was made of the more common flat cable insulations including polyesters, polyvinylchloride, (PVC), fluorinated ethylene propylene (FEP), polytetrafluoroethylene (PTFE), and polyimide. In this analysis, a known mass of material is exposed to increased temperatures until the mass is completely vaporized with a mass versus temperature recording made to observe their relationship (Figs. 7, 8, and 9).

RESULTS

The results to date have revealed that (1) bond parameters are within reasonable working values, (2) successful bond formation between conductor materials has been achieved, and (3) its capability of bonding through various conductor insulations.

Minimum bond parameters required were temperatures between 50 and 60 percent of the conductor melting point, with pressures in excess by approximately 2 to 1 of the materials yield strength. Times were minimal, falling between 3 and 9 seconds per set of bonds. Utilizing the minimum bond requirements caused approximately 40-percent material deformation for the test sample configurations used. For each material tested, there existed an optimum set of bond conditions. If excessive values of pressure and temperature were utilized, a necked-down condition occurred between the joined area and lead which became the mode of failure. This necking action was reduced by proper ram face design, providing for a radiused condition at the transition point.

Test data indicated that successful bonds were obtained with various like metals including copper, beryllium copper, phosphor, bronze, brass, Kovar, aluminum, and combinations of unlike metals including copper, beryllium copper and phosphor bronze. (Figs. 2b, 10, 11, and 12) Also, gold- and silver-plated copper conductor were successfully joined (Fig. 13).

Mechanical characteristics of such joints exhibited a tensile strength of 85 to 90 percent and peel strengths of 50 percent of the tensile strength of a virgin metal lead. However, microsectioned samples indicated that the peel test was more indicative of a good bond than a tensile test. A sample with good peel strength characteristics did not exhibit distinctive boundary line at the joint interface because of sufficient diffusion and grain growth occurring while good tensile strength could be obtained in samples having a very distinctive boundary line. This is because during tensile tests all bonded contact points are in a shear condition simultaneously, and under peel conditions only a portion of the bonded contact points are under tension at a given time, allowing for

successive failures along the joint interface. With good peel strengths, the number of bond contact points are at a maximum (Figs. 2a and 2b).

Photomicrographs of sample cross-sections (Figs. 2a and 2b) indicated that with good peel strength the boundary line became nonexistent, that there was some grain growth occurring during the bond operation, and that there was some oxide pockets, approximately 31 microns in diameter, throughout the bonded region. Neither the grain growth nor oxide pockets were found to be sufficient to create problems.

The microhardness tests indicated a very constant degree of hardness across the bond portion, indicating an absence of brittle intermetallic formation. Also, the microprobe analysis indicated consistent composition across the bonded portion. The electrical characteristics indicated contact resistance in the microohm region (150 μ-Ω for copper) with current capacity not yet tested.

As stated earlier, various comparisons were made between EPB joints and those soldered, resistance welded, and crimped. For peel strength comparisons, EPB bonds had a value of three to four times greater than solder and equivalent to welded joints. For contact resistance, EPB bonds had approximately one-half that of equivalent crimped joints and were about 10 percent lower than the welded or soldered joints. Also, the contact resistance for EPB joints was much more stable than crimped joints.

Comparing the speed of joining of the various techniques, it would appear that EPB is approximately equal to crimping and reflow soldering methods. However, if one considers the time required to remove the dielectric prior to the soldering operation, EPB is clearly faster. EPB joining is much faster than resistance welding techniques for multijoint applications such as flat conductor cable.

The results from the Thermo-Gravimetric Analysis indicates a variety of temperatures are required for insulation removal. Regular polyester (Fig. 7) and FEP were found to be relatively unstable and to have complete weight loss in air at approximately 600°C, but polyimide (H-FEP) required temperatures as high as 1020°C (Fig. 8). The other two insulations tested, PVC and a flame retardant polyester (Fig. 9), leave a residue (5 and 10 percent by weight, respectively) at 600°C and did not have a complete weight loss even at 1000°C.

The rams used at present are capable of operating to 700°C with no detrimental effects and have been successful in bonding flat conductor cable with insulations of both polyester and FEP. The flame retardent polyester does have

a residue, but it has not been found to be detrimental, even to insulation resistance. New bonding heads are being constructed of a higher temperature material which will allow bonding through the polyimide insulation. Results from bonds through PVC have not yet been received from our laboratories. Future tests on EPB joints are to include thermal shock, vibration, and effects of industrial atmospheres.

The initial bonded joints for flat cable have been made in bonding flat conductor cable to flat conductor cable and have been very successful with a minimal amount of fixturing for aligning the conductors. Here, there are actually four layers of conductor insulation to penetrate as compared to two in making joints between flat cable and bare contacts. The flat conductor does lend itself most readily to this technique where for round conductors, both solid and stranded, the holding and aligning fixture does become more sophisticated but, with proper ram design, it appears that the technique will be applicable. Flat conductor cable with conductor densities of 0.050-inch pitch has been bonded with no particular problems and it is believed that this technique will be applicable for center-to-center spacing of 0.025 inch.

SUMMARY AND CONCLUSIONS

The purpose of this paper was to describe a bonding technique which would fill the voids left by other methods such as soldering, resistance welding, and crimping. The results have indicated at least one major advantage of EPB over other techniques and as yet no real major disadvantages. The results also indicate that the process is feasible, its operation is realistic for production oriented bonding, and that a wide range of applications does exist for such a technique, especially in terminating flat cable either to other cable or to connecting devices.

The process has indicated capabilities for:

1. Joining of a wide range of like conductor materials.
2. Joining of a range of dissimilar metals.
3. Joining of metals through thin layers of contaminants.
4. Joining of conductors through insulations.
5. Multiple joining of conductors simultaneously.

6. Joining conductors of various geometries.

7. Joining of conductors with densities of 0.050 inch on centers.

This system at present is not portable, but one design goal is to develop a system to be used for field terminations and repair. Also, along with this investigation, Bendix is developing a high density flat cable connector incorporating this termination technique along with other unique features.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Dr. Seong K. Rhee of Bendix Research Laboratories for his valuable assistance and advice in the preparation of this technical paper on energy pulse bonding.

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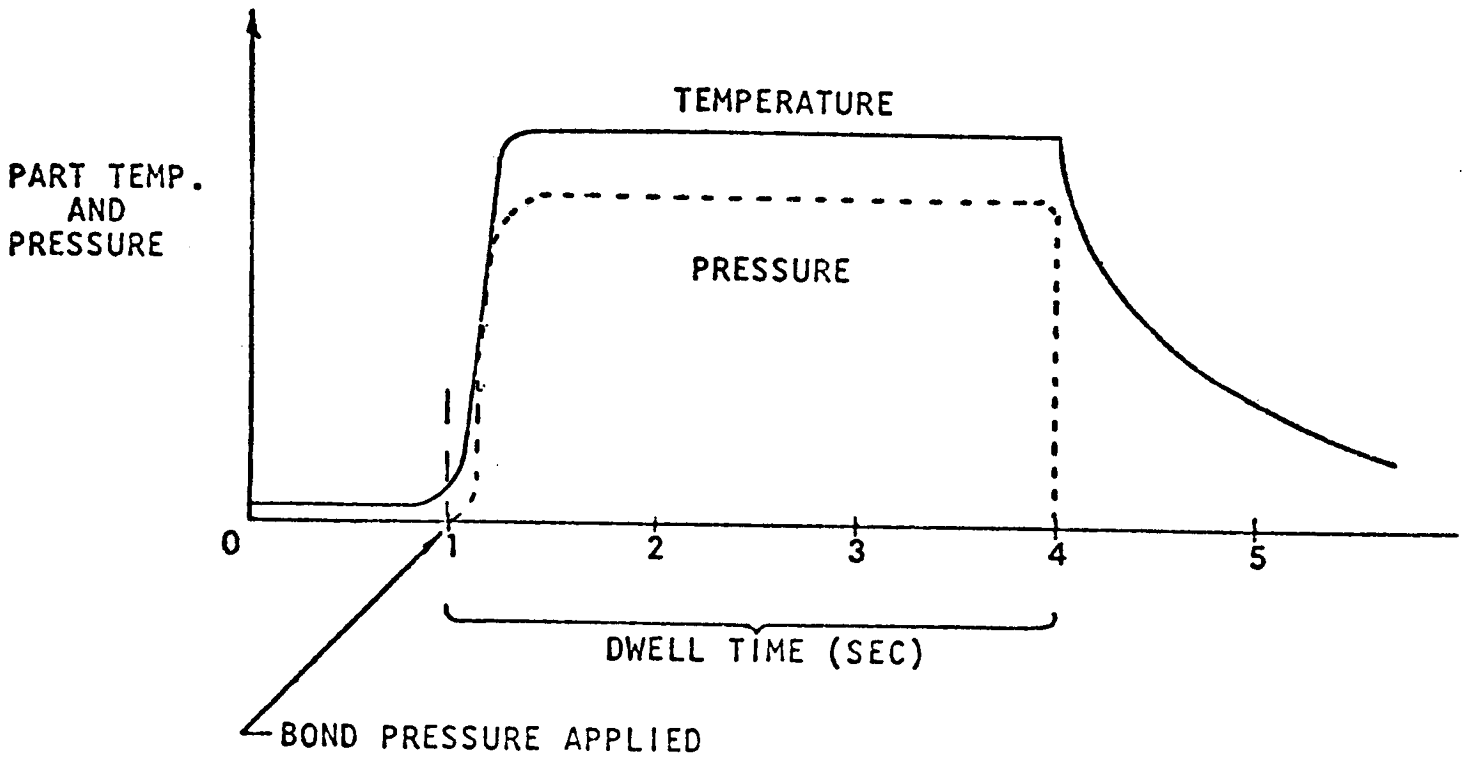
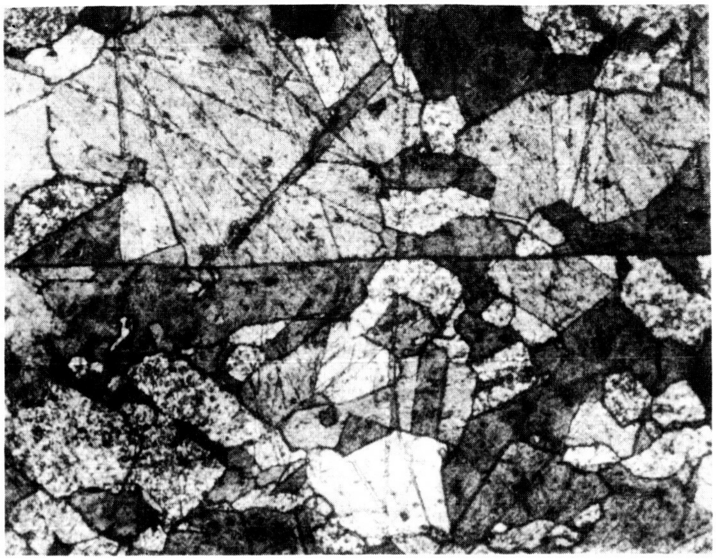


Figure 1. Energy pulse.

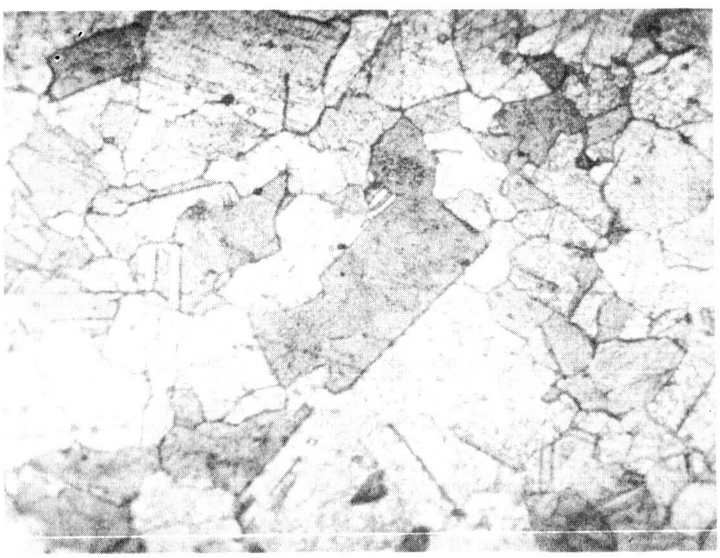


MAGNIFICATION – X 400

BOND TEMPERATURE – 1210° F

BOND TIME – 5 SEC

BOND PRESSURE – 20 000 psi



MAGNIFICATION – X 400

BOND TEMPERATURE – 1210° F

BOND TIME – 5 SEC

BOND PRESSURE – 58 000 psi

Figure 2. Cross section of copper-to-copper bond.

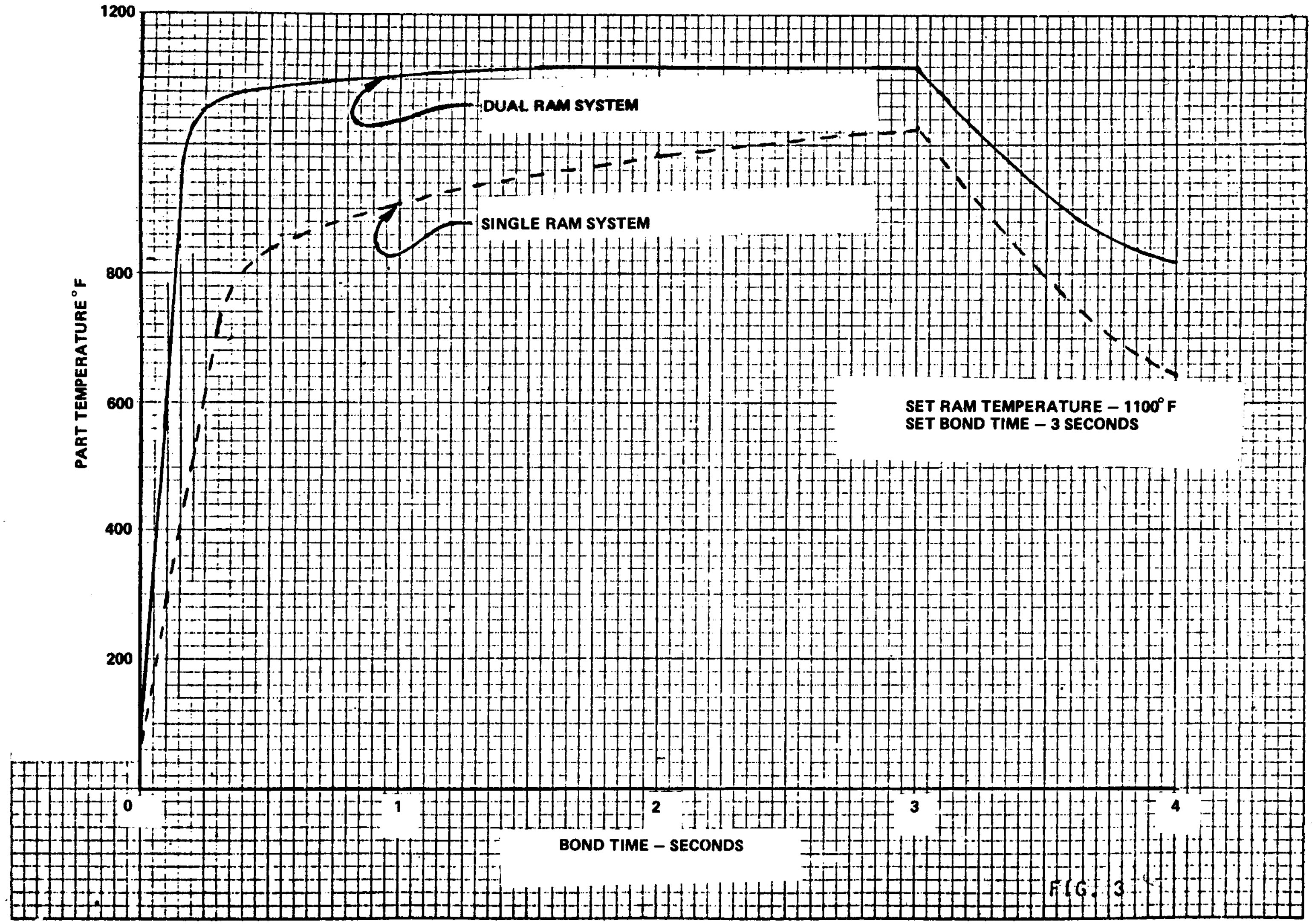


Figure 3. Dual ram.

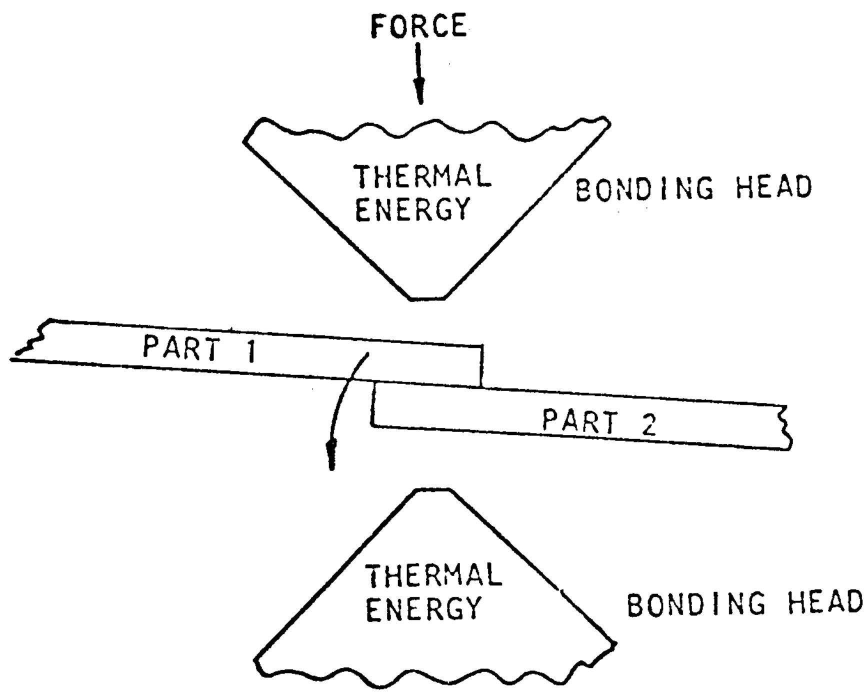


Figure 4. Dual head system and work parts.

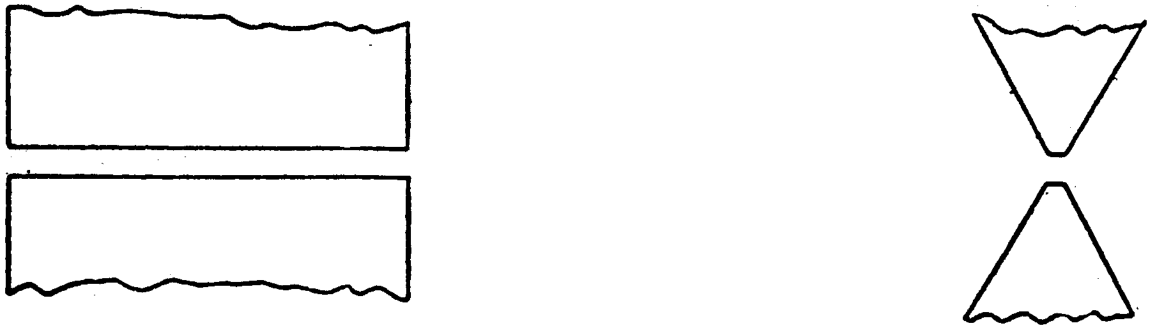


Figure 5a. Flat surface bonding heads.

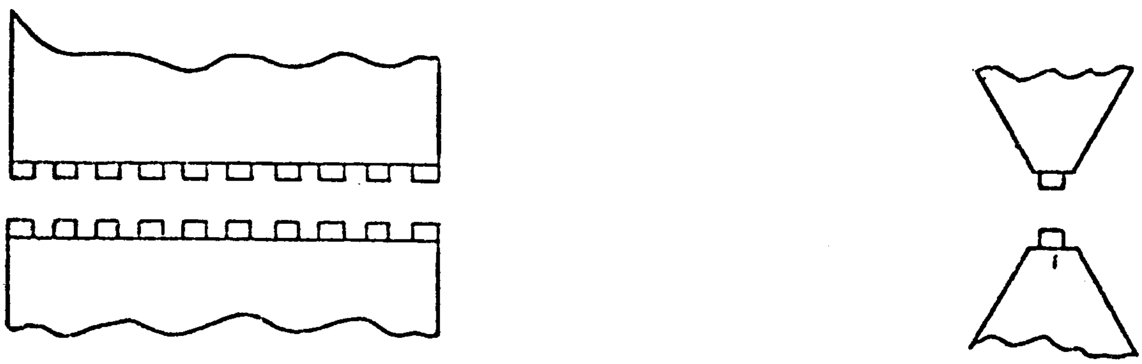


Figure 5b. Protrusions on both bonding heads.

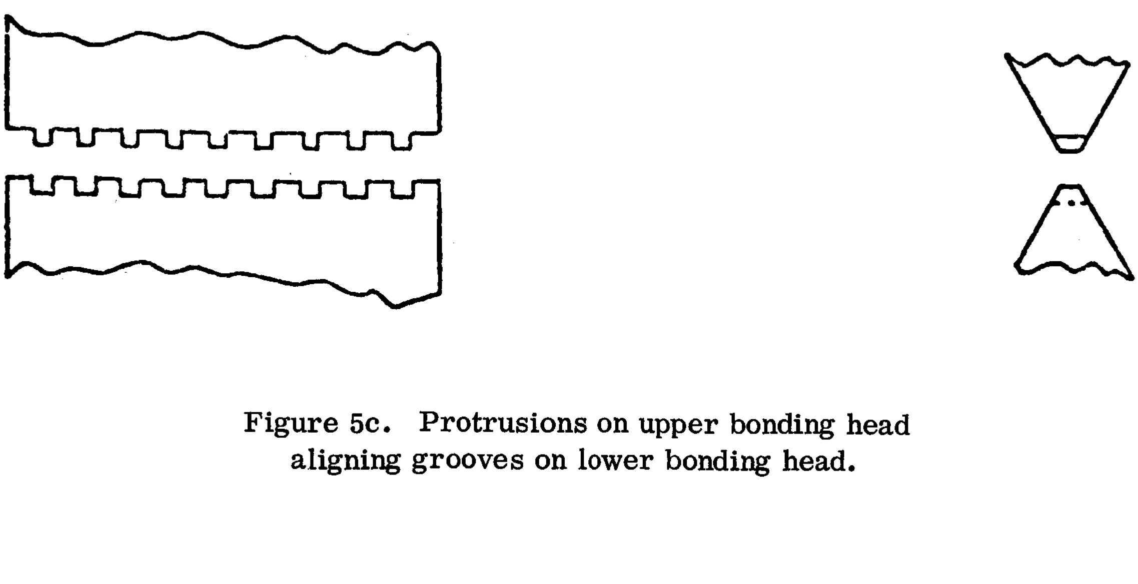


Figure 5c. Protrusions on upper bonding head aligning grooves on lower bonding head.

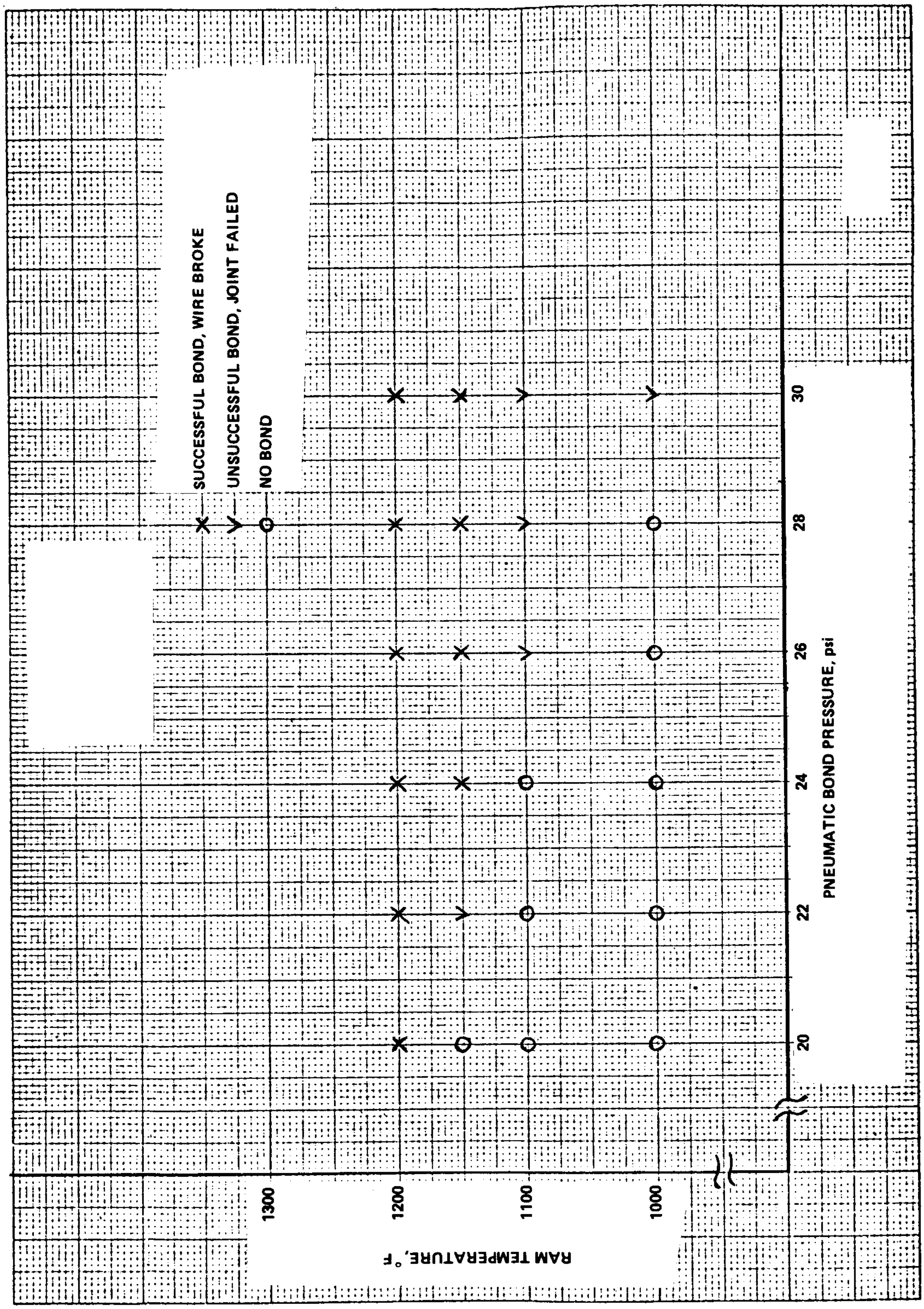


Figure 6. Tensile data for Kovar to Kovar.

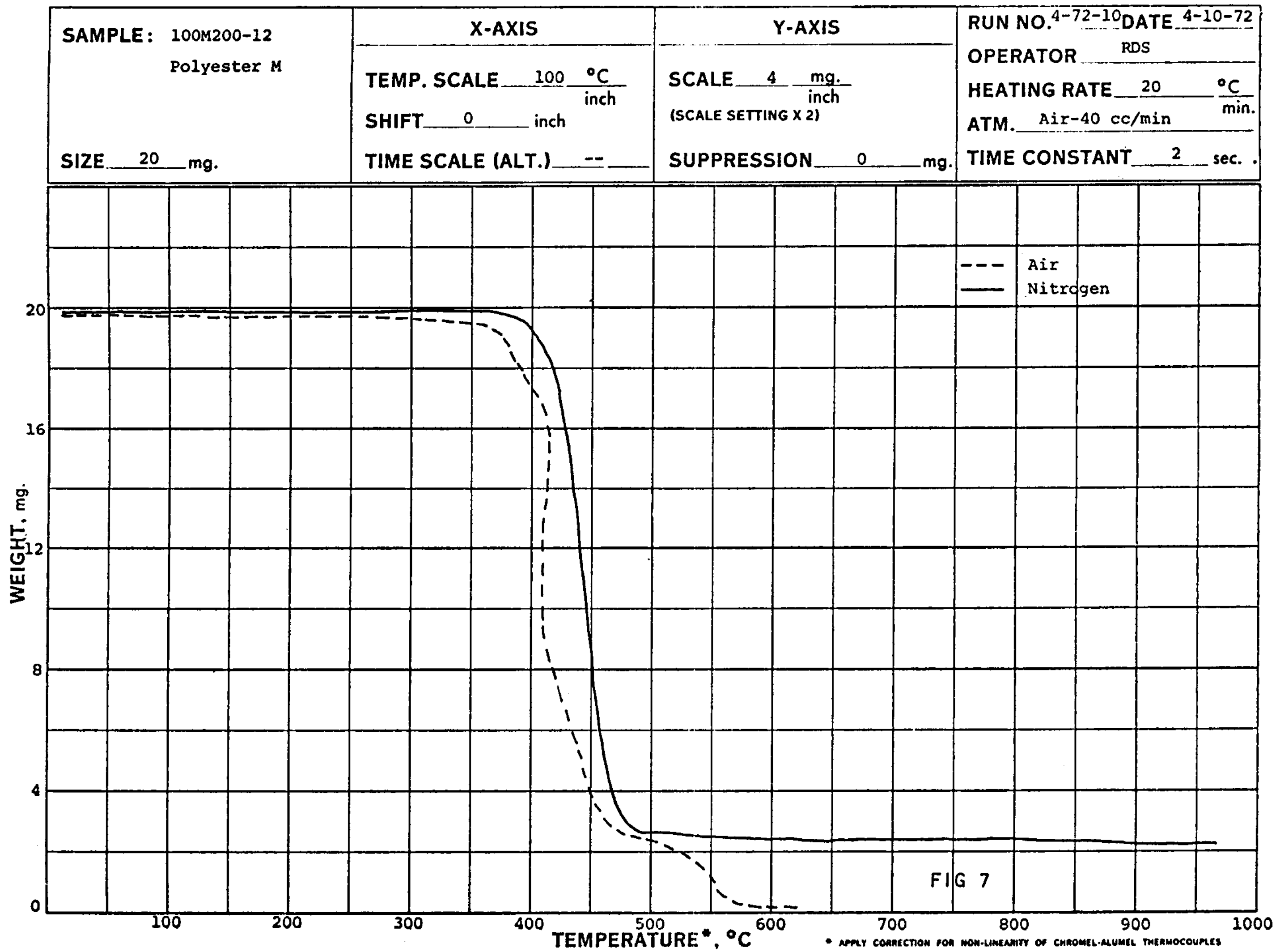


Figure 7. Polyester temperature versus weight.

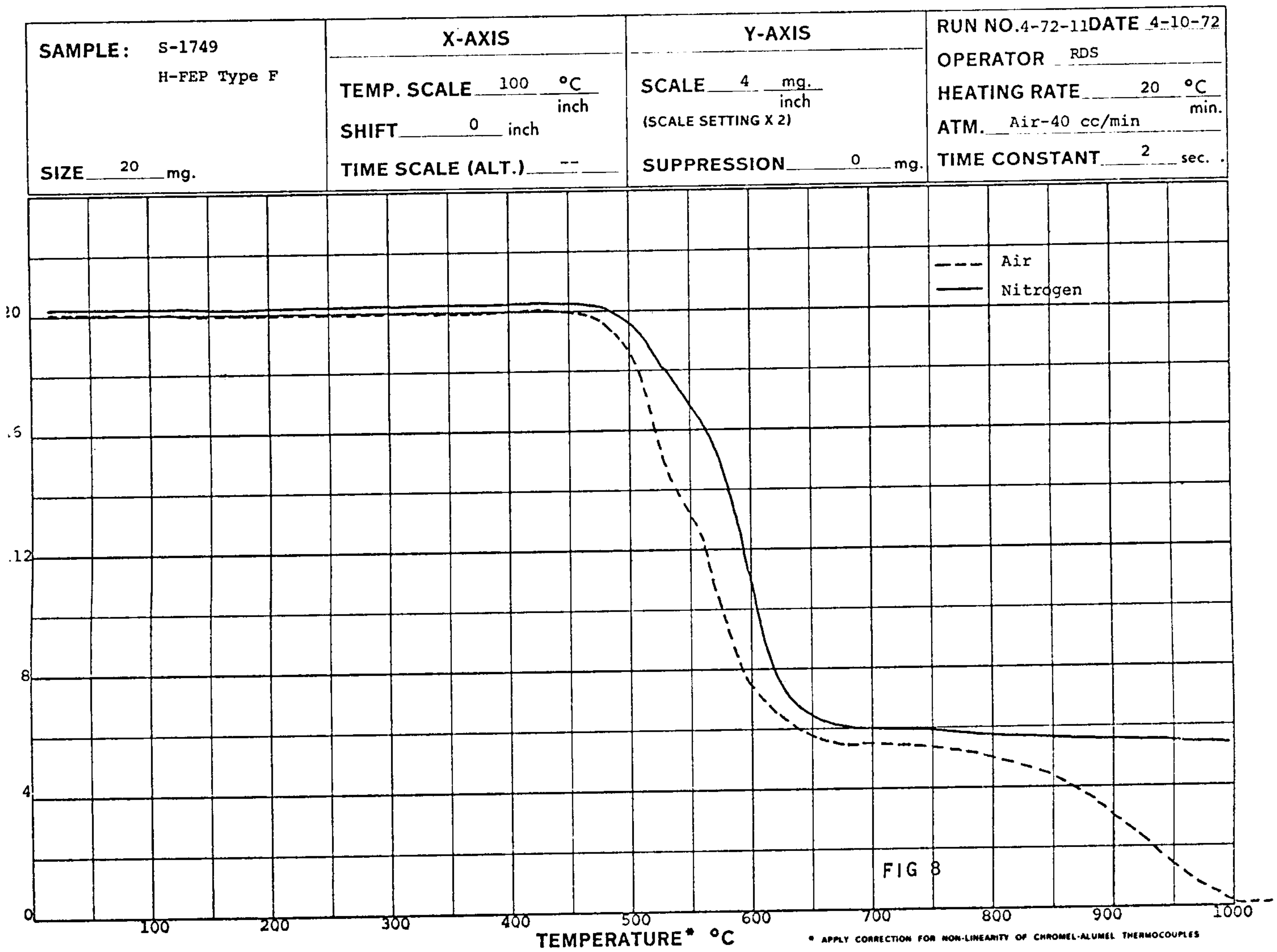


Figure 8. H-FEP Type F, temperature versus weight.

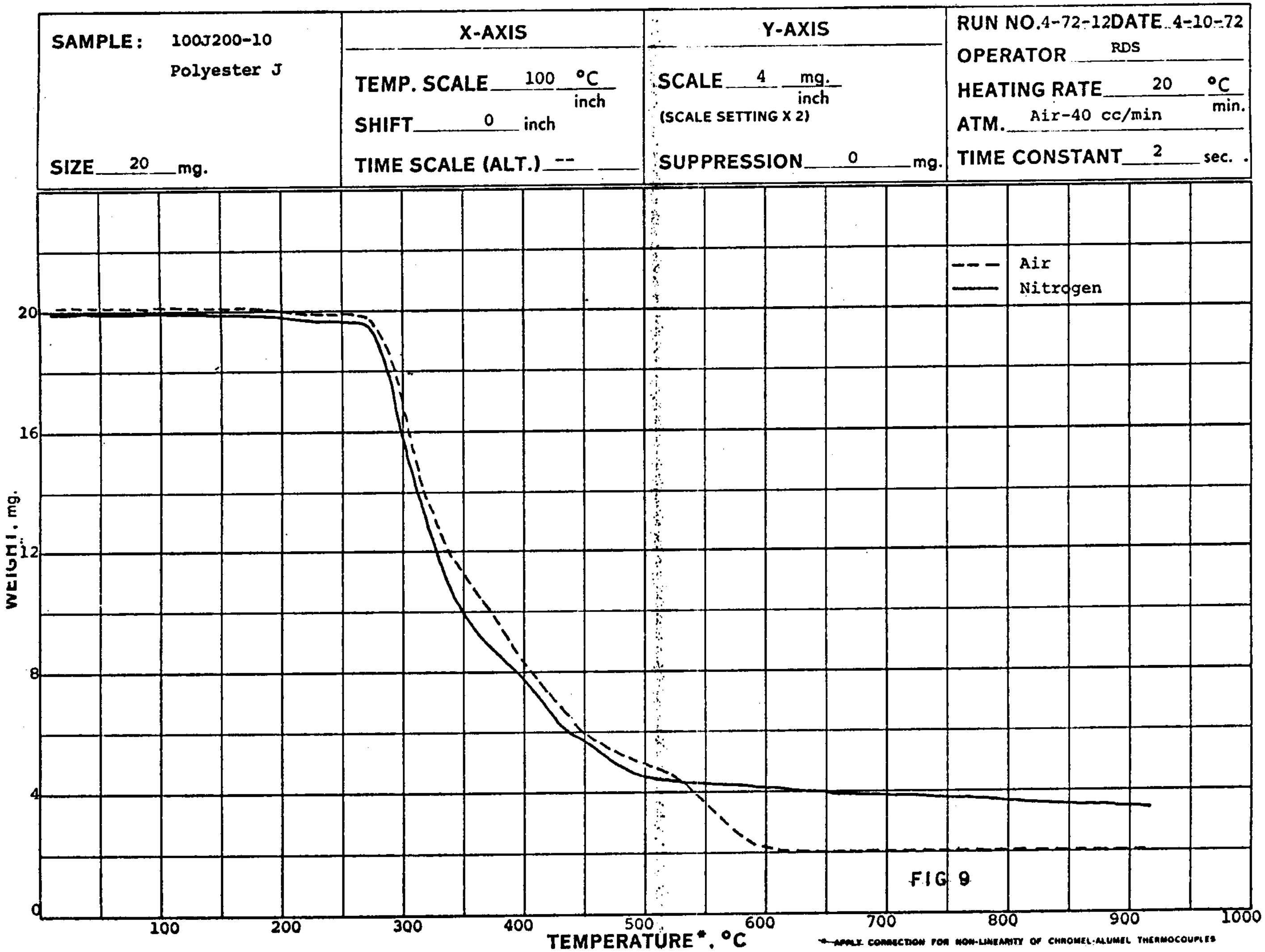
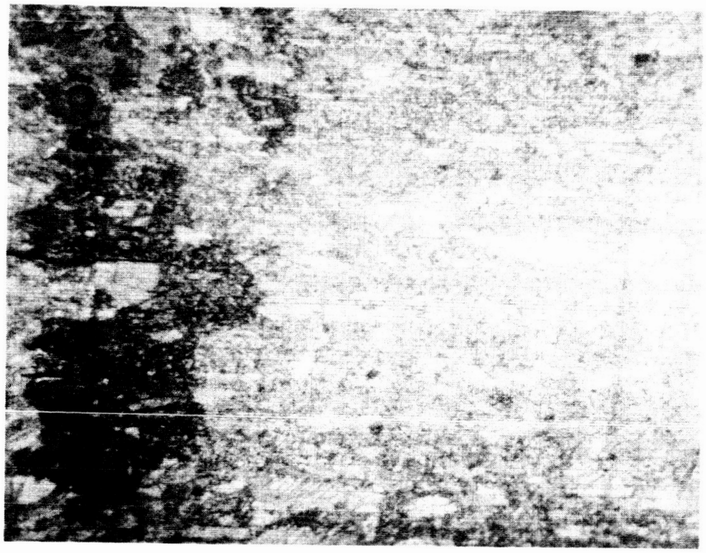


Figure 9. Polyester J, temperature versus weight.



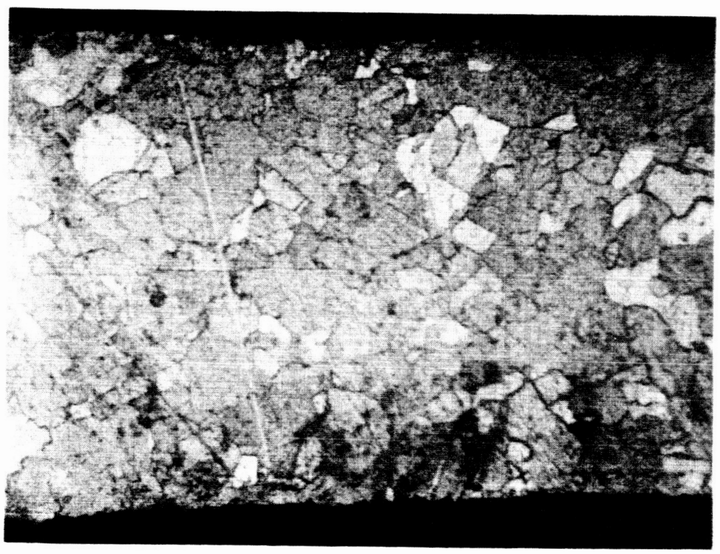
MAGNIFICATION – X 400

BOND TEMPERATURE – 1000° F

BOND TIME – 5 SEC

BOND PRESSURE – 148 000 psi

Figure 10. Cross section of BeCu-to-BeCu bond.



MAGNIFICATION – X 400

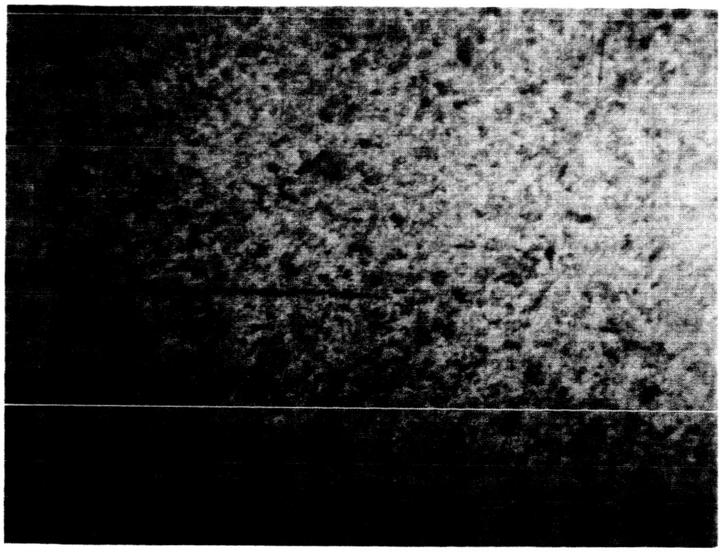
BOND TEMPERATURE – 1200° F

BOND TIME – 9.9 SEC

BOND PRESSURE – 148 --

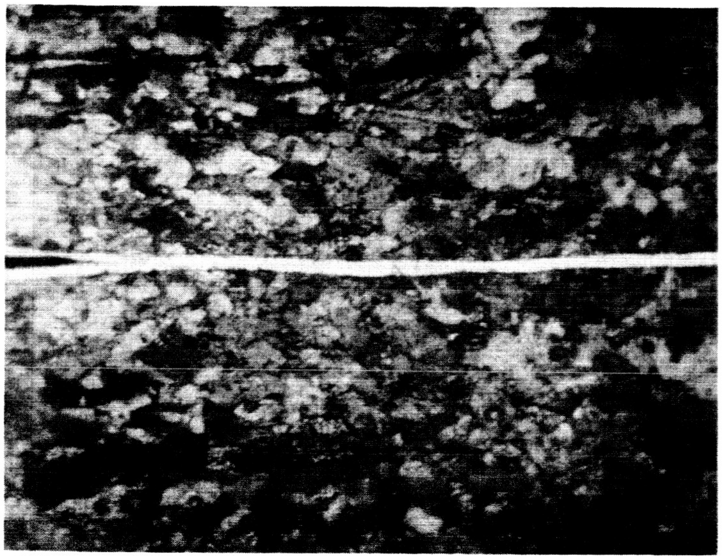
BOND PRESSURE – 148 000 psi

Figure 11. Cross section of brass-to-brass bond.



MAGNIFICATION – X 400
BOND TEMPERATURE – 600° F
BOND TIME – 3 SEC
BOND PRESSURE – 34 000 psi

Figure 12. Cross section of AL-to-AL bond.



MAGNIFICATION – X 400
BOND TEMPERATURE – 1050° F
BOND TIME – 3 SEC
BOND PRESSURE – 30 000 psi
CONDUCTORS – AG PLATED Cu
INSULATION – FEP

Figure 13. Cross section of FCC to FCC.

TRANSITION SPLICES AND COST COMPARISON

By M. D. Remedios
The Boeing Company

FCC TRANSITION SPLICES

by M. D'Almada Remedios

THE BOEING COMPANY
Commercial Airplane Group

INTRODUCTION

The Boeing Company has, for the past several years, conducted studies in Flat Conductor Cable (FCC) and its possible applications in commercial airplanes. The program included investigations into cable geometry and insulation characteristics; terminations and connectors; installation and routing techniques; applications in general purpose wiring; applications of flat power cables, and system applications with the use of Matrix Interconnection Centers (MIC).

In production, we have a special application in the upper deck passenger entertainment system wiring of the 747 airplane. The upper deck does not have a floor suitable for wiring and accordingly an "under the carpet" installation, demanding a very low profile, was considered necessary. FCC met this requirement. FCC harnesses with breakouts to each lounge seat were transitioned to RWC to accommodate existing round connectors. A considerable amount of testing was carried out to verify the integrity of the cable, fold and transition joints, and a mechanical test (sheep's foot test) to ensure that the FCC and fold area will withstand the punishment of being walked-upon by stiletto heels (100 impacts at 2400 psi). Problems were encountered with manufactured parts and subsequently improved processes were used to comply with these test conditions.

The experience and service results indicate that transitions are required and can be satisfactorily accomplished but new techniques are required. The transition splices developed at that time were limited to shop floor production requiring "clean" conditions, high temperature (350°F) and pressure (900 psi). It comprised of layering Kapton and Reigal adhesive and compressing the layers at temperature. These parts were, therefore, categorized as non-maintainable.

In a recent program with NASA-MSC (Contract NAS9-12062) two designs of transition splices were developed and tested (the development is reported in Vol. 1 of D6-40711). The two splices have been designated "Boxed" splice and "MTSM" (Multiple Termination Splice Module).

The design goal was to produce splice terminations that are electrically insulated to withstand the environmental conditions and are capable of being repaired and reworked on installed cables with the use of hand tools.

Insulation-Piercing Crimp and "Box" Encapsulation

This concept is detailed in Figures 1 through 3.

This design goal was met by the selection of the A-MP Unit insulation crimp-through contact. To meet the requirements, an FCC-to-FCC "link" and an FCC-to-RCC "link" were required. The FCC bridge crimp was fabricated by using solder tabs cut and welded together to form the joining link.

The FCC-to-RCC link was fabricated by using solder tabs (FCC side) and socket contacts (RCC side) and soldering the contacts.

Crimping of the FCC contacts is economically and effectively carried out on the A-MP automatic FCC crimp machine. A prototype hand crimp tool is also available.

The two box halves, designed to encase the terminations were molded from diallyl phthalate which has a satisfactory record in its application in connectors where good electrical properties at high temperature are required.

Problems

The diallyl selected proved to be tough but brittle, but it was committed for production of test hardware. In an endeavor to provide data for future application, sample boxes were molded with diallyl having long glass fibers. This showed very slight improvement. However, parts molded with diallyl reinforced with glass cloth showed significant improvement but was projected to be costly.

Prototype boxes machined from Tefzel were obtained. These were tough and very flexible; however, bonding was a problem.

The splice contacts used are longer than required; accordingly, the box length can be reduced significantly and a more compact arrangement obtained in the production splices with shorter bridge contacts.

Multiple Termination Splice Module (MTSM)

This concept uses the solder sleeve and heat-shrinkable sleeve. The heat-shrinkable sleeve was made from transparent, irradiated, cross-linked, heat-recoverable, polyvinylidene fluoride (Kynar) sheet bonded together and formed into a flat configuration to provide individual conductor cavities and a sheath at each end. Each cavity contained a preformed, soft ETP copper 110 interconnecting insert previously coated with a calculated amount of solder and flux. Each sheath was lined with a fusible material (Hytrel, a DuPont product), which melts and flows when heat is applied. Therefore, the sheath isolates and the Hytrel seals each individual soldered termination.

Details of this concept are in figures 4 through 6.

For a branch circuit or a repair splice, a single solder sleeve would be used. The details of this splice are clearly shown in figure 7.

Figure 8 shows various branch circuits for FCC and RCC and also ribbon wire.

Problems

Failures with early test samples were caused by partial unbonding of the dielectric (Kynar) web between adjacent splices, pinholes in the MTSM jacket caused by misalignment of the heating tool, and sharp corners in the presolder splice insert. Improvements were immediately made by the suppliers in the redesign of the metal insert and tooling.

TEST PROGRAM

Ten samples of each splice, FCC to FCC and FCC to RWC, of each concept were subjected to the following environments and tests:

Thermal Shock - 5 continuous cycles at -55°C ± 5°C and 135°C ± 5°C (for boxed splice) or 125°C ± 5°C (for MTSM) for 30 minutes at each temperature.

Vibration - random vibration for not less than 1 hour per axis, as follows: acceleration spectral density increasing at a rate of 3 db/octave from 20 to 200 Hz; constant at 0.06 g^2/Hz from 200 to 1200 Hz and decreasing at a rate of 3 dB/octave from 1200 Hz to 200 Hz. (This test had been carried out previously on a similar "make-up" and was not conducted in this program.)

Thermal Aging - The applicable samples were placed in a circulating air oven stabilized at 135° ± 2°C (boxed splice) or 125° ± 2°C (MTSM) for 96 hours.

Moisture Resistance - Five 24 hour cycles with each cycle comprising of 2 eight hour excursions from 25°C to 65°C (held for 3 hours at 65°C and 90 - 98 % relative humidity) rise and fall time, 2 1/2 hours with relative humidity 80 - 90% and a third excursion to -10°C held for 3 hours.

Salt Fog - Samples subjected to 5% salt solution for 48 hours.

Tests were conducted at the start of the program and after each environment exposure with measurements for electrical conductivity, voltage drop, dielectric withstand voltage and insulation resistance.

Test Results

The FCC used in all the test samples are 2 inch wide with 19 conductors (0.004 x 0.065 of ETP unplated copper) at 0.1 inch centers and insulated with 3 mil FEP and 1 mil Kapton. Conductors for each test sample were numbered 1 to 19 and 1, 4, 12 & 14 were each used as sensing leads to monitor the mvd across the splice junctions of conductors 2, 5, 13 & 15 respectively.

Summary of test data are given in Table 1 and 2 for the Boxed Splice and Table 3 and 4 for the MTSM.

Both concepts show feasibility of fulfilling the requirements of a permanent splice.

The advantages of automatic crimping at a high rate is a strong motivation to pursue the crimp approach. The higher splice resistance is acceptable provided it is repeatable and remains stable.

The MTSM concept has a very acceptable level of splice resistance and is stable. Some delamination of the insulation after environmental exposure was experienced and improvements in fabrication techniques should eliminate the problem.

Additional work is being done to refine the processes and materials in both concepts.

Another promising approach is being pursued. This is the concept of ultrasonic welding of the conductor, the insulation and the insulated box or housing.

As can be seen from figure 9, this approach would require stripping cable on one side only, with some additional preparation of the conductor and the insulation. The two cables, with the conductors exposed, are placed together (bare conductor against bare conductor) in a housing and captivated in an ultrasonic "head". The ultrasonic cycle for welding the conductors together is applied. This is then followed by the application of another predetermined frequency for welding the insulation and the box housing together to give a totally sealed connector/junction. This approach has exciting possibilities and would contribute to the utilization of Flat Conductor Cable.

Acknowledgements:

Messrs. Lyle White and Leroy Proctor, NASA-MSC, technical direction

Amp. Inc., and Raytheon Corp. participated in the program.

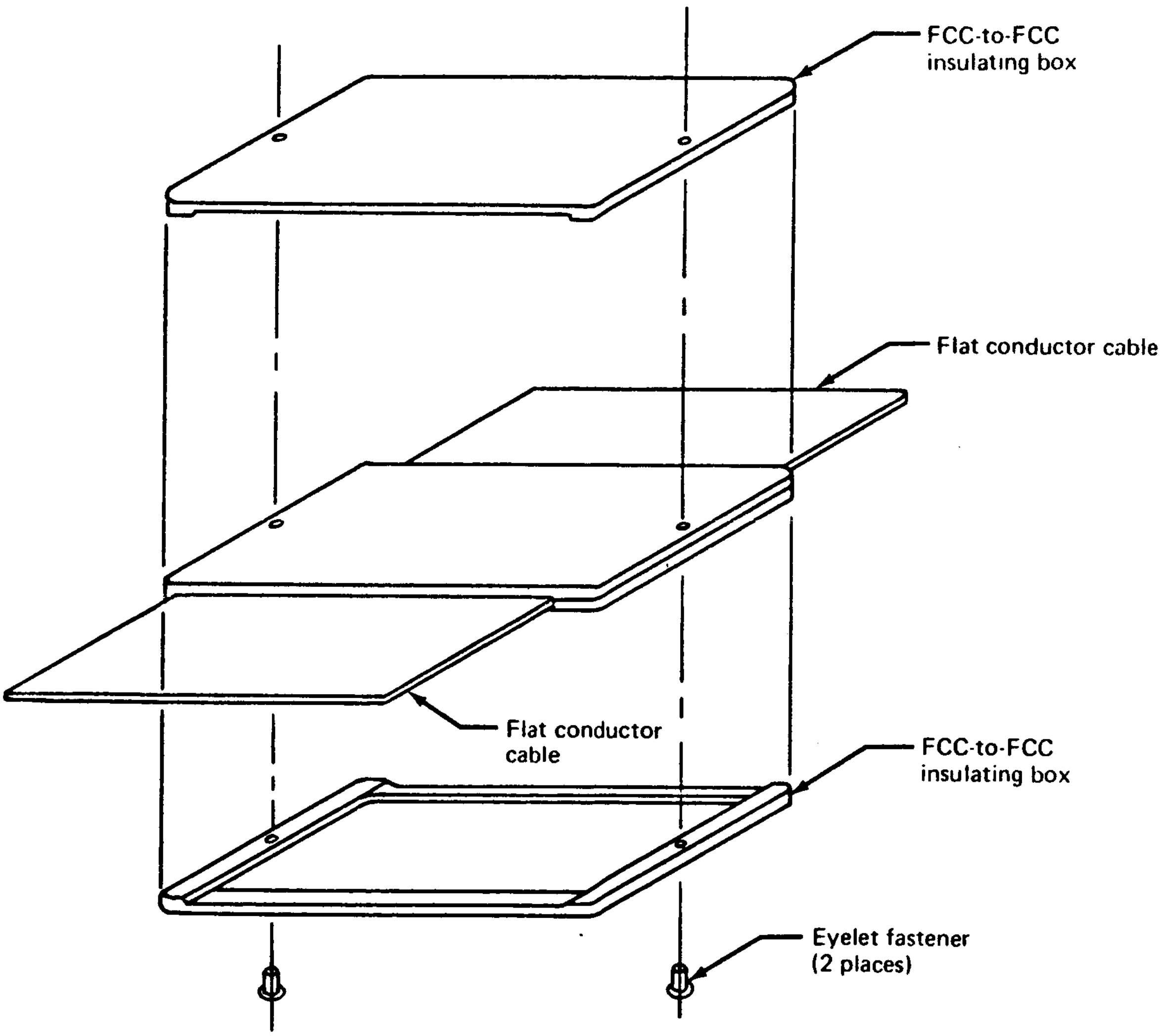


FIGURE 1.—EXPLODED VIEW OF COMPONENTS—FCC TO FCC

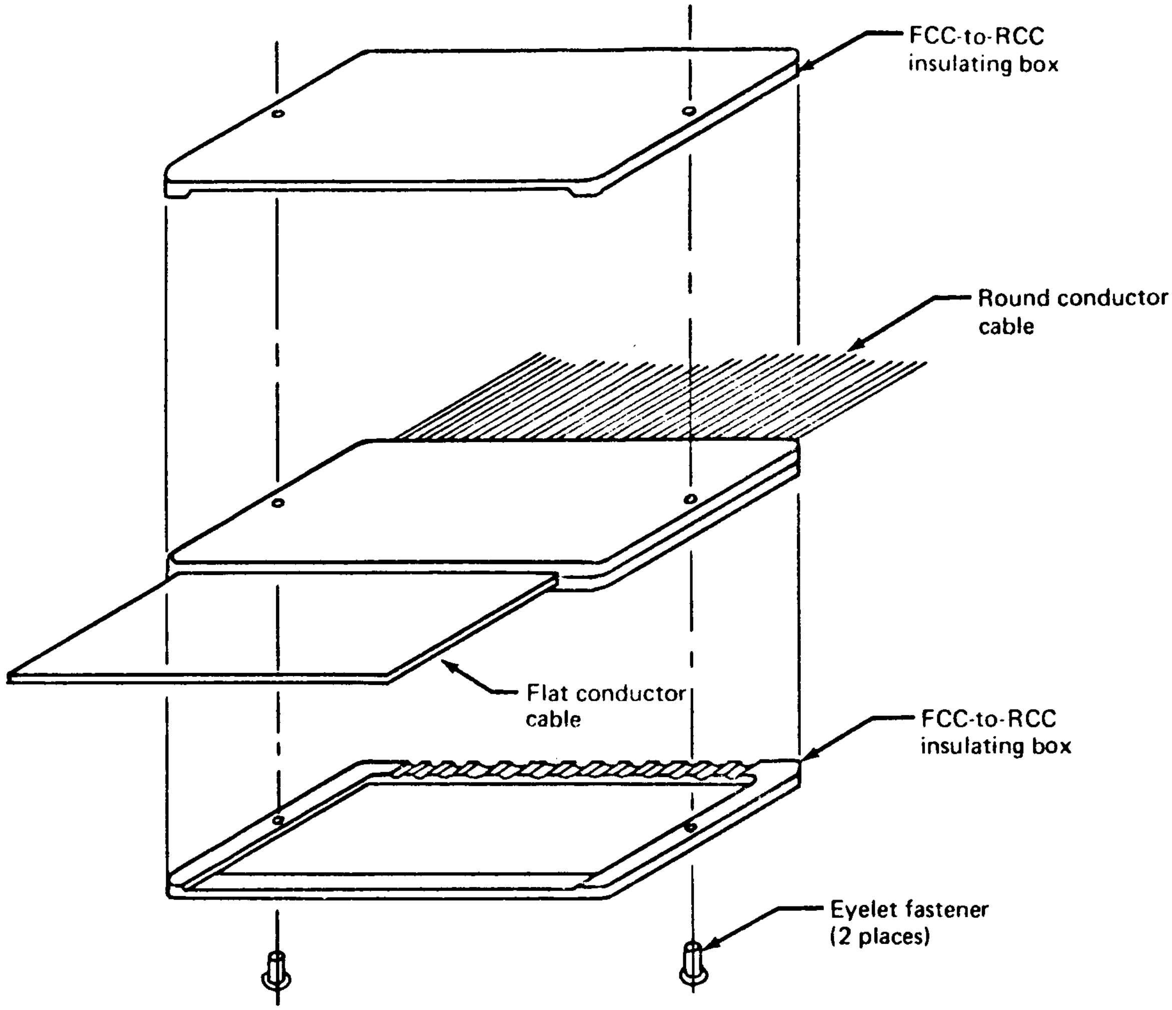


FIGURE 2.–EXPLODED VIEW OF COMPONENTS–FCC TO RCC

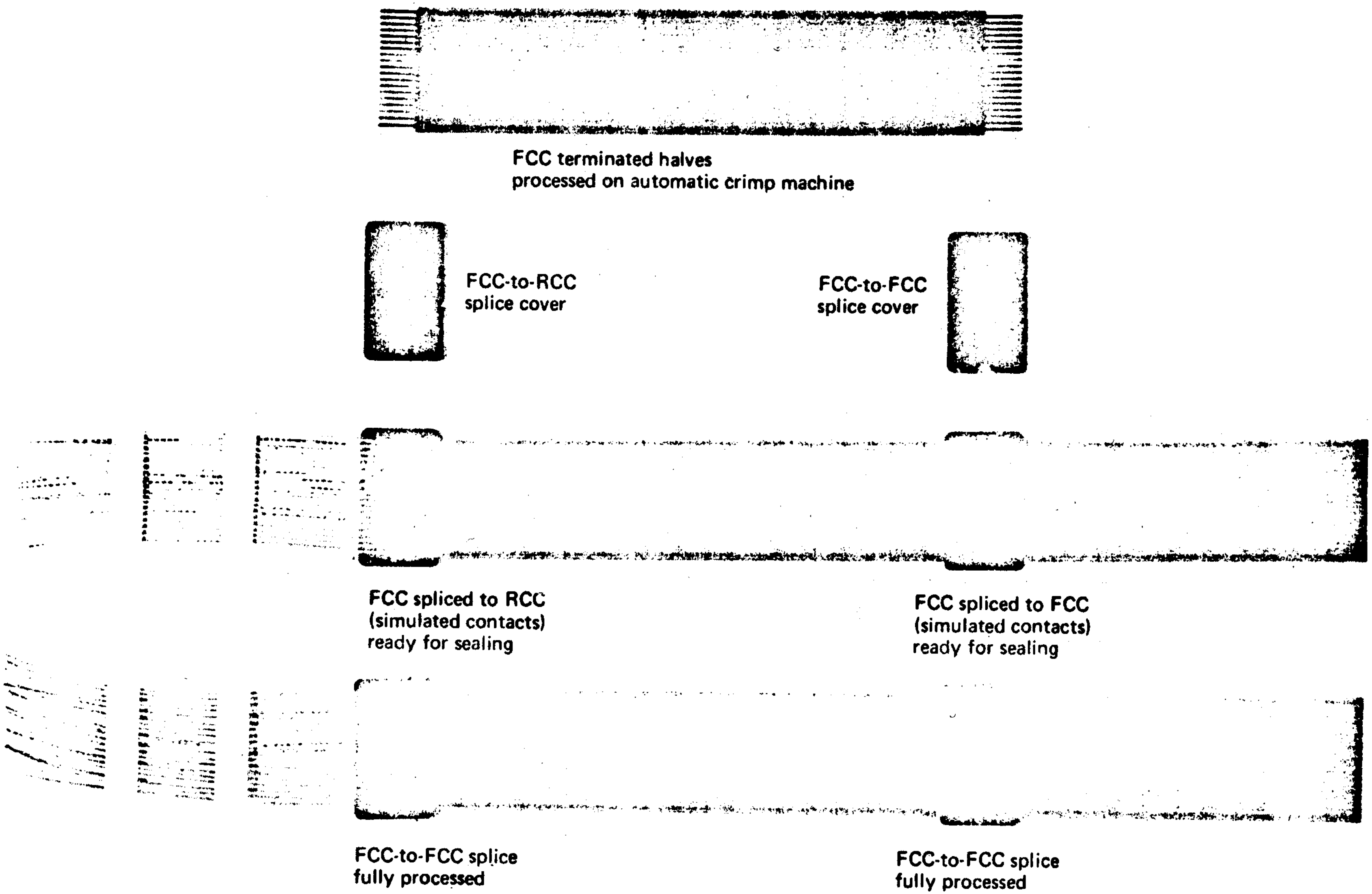


FIGURE 3 —COMPONENTS IN VARIOUS STAGES OF ASSEMBLY—FCC TO FCC AND FCC TO RCC

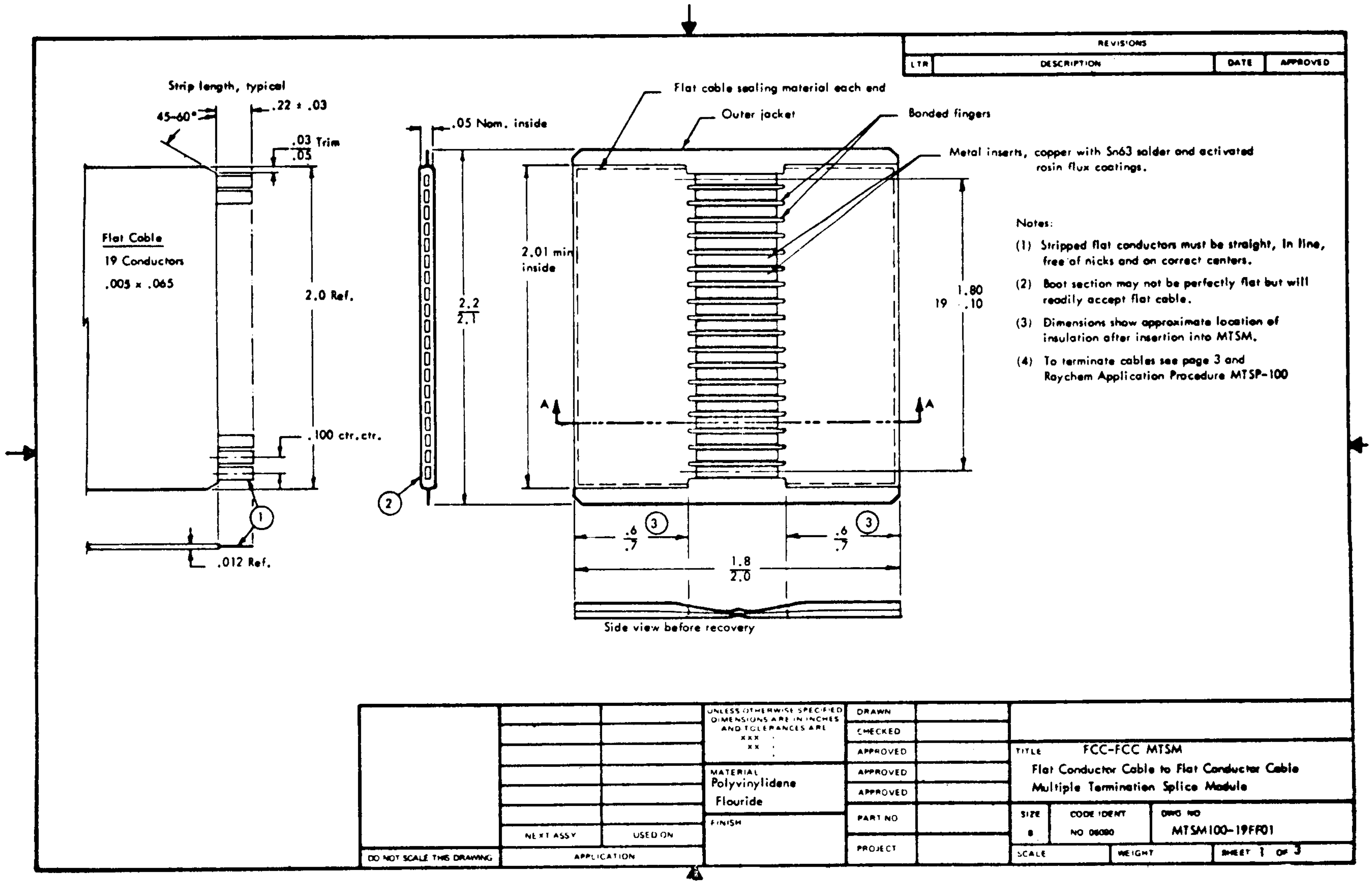


FIGURE 4.—FCC-TO-FCC MODULE (RAYCHEM DRAWING)

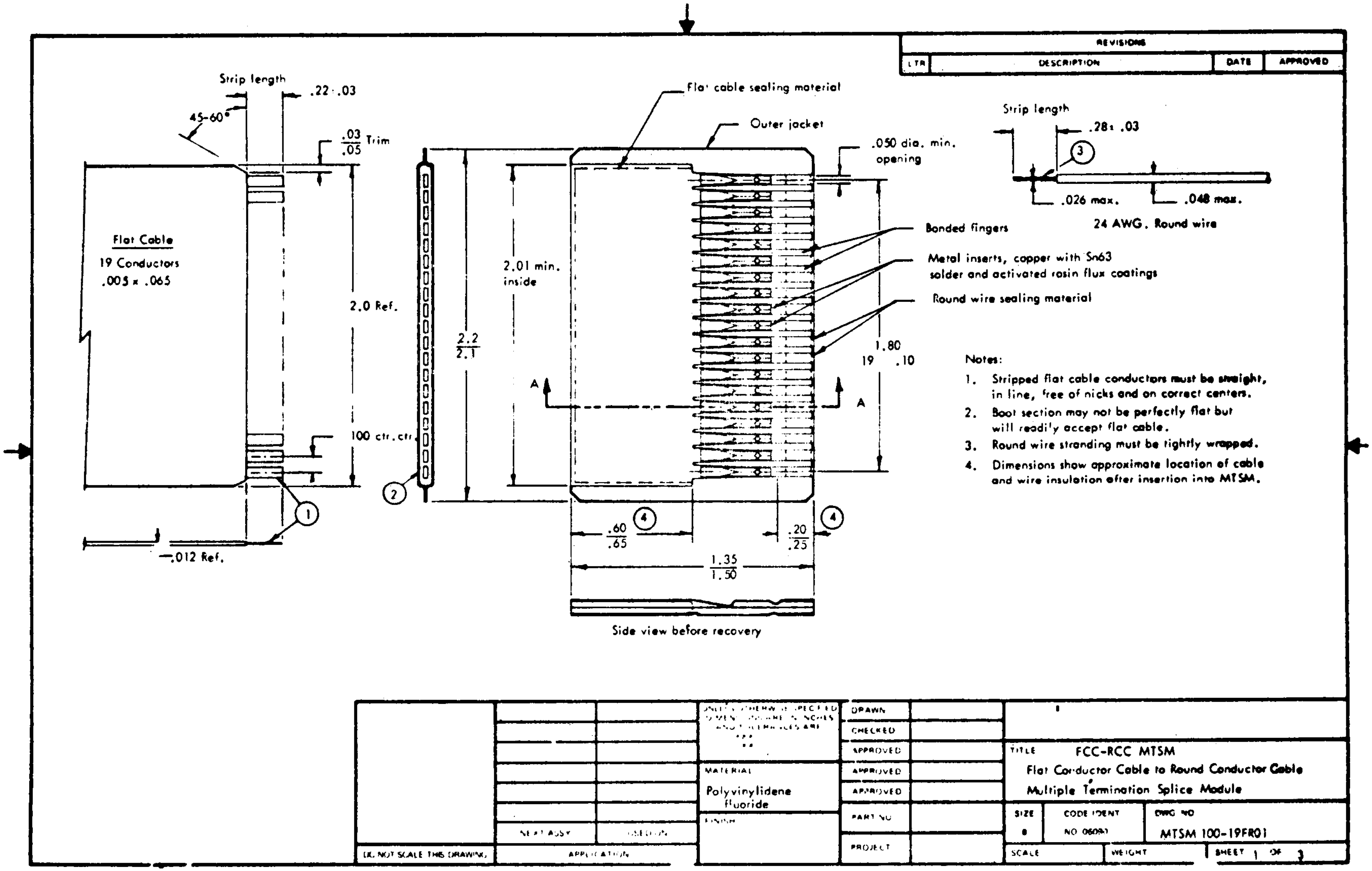


FIGURE 5 —FCC-TO-RCC MODULE (RAYCHEM DRAWING)

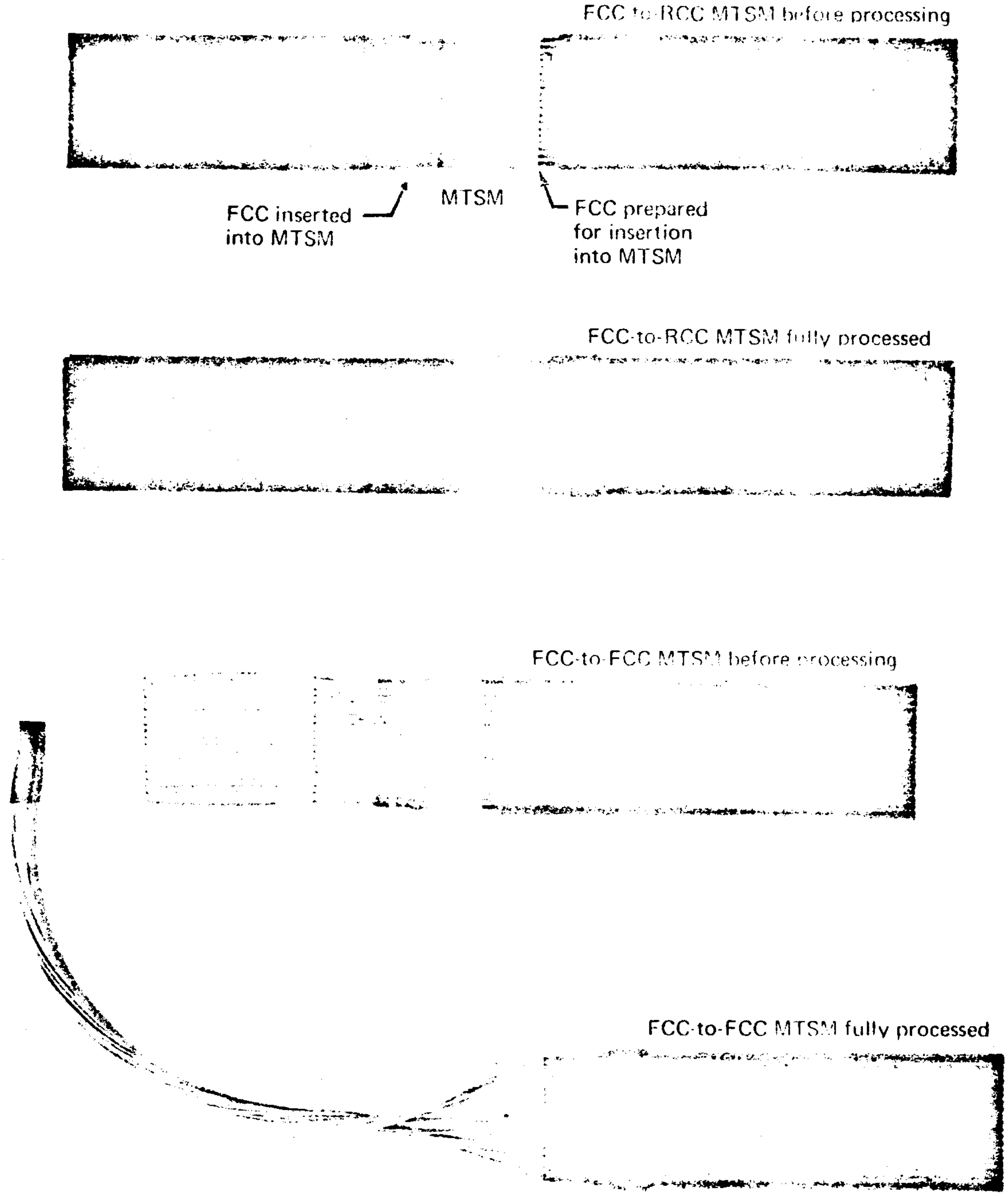


FIGURE 6 —COMPONENTS IN VARIOUS STAGES OF ASSEMBLY— FCC TO FCC AND FCC TO RCC

(1) Insulation sleeve
Heat shrinkable, radiation cross-linked, modified polyvinylidene fluoride, transparent blue.

(2) Flux-filled solder preform
Sn 63 RAP 2 per Federal Specification QQ-S-571.

(3) Sealing rings
Modified thermoplastic.

(4) Buss bar
Copper alloy coated with Sn 63 alloy and noncorrosive activated flux.

Notes:

This part is designed for use with FCC having 0.065-in.-wide conductors on 0.100-in. centers such as M55543/19-H4E19. It may be used to splice the individual conductors or to make breakouts to individual wires or flat cables having either round conductors (24 gage max) or flat conductors (0.065-in. wide max).

Acceptance sampling shall be in accordance with MIL-STD-105. The acceptable quality level (AQL) shall be 4.0.

The FCC must be prepared by slitting the conductor to be spliced and adding the branch circuit. The transition is processed by the application of heat.

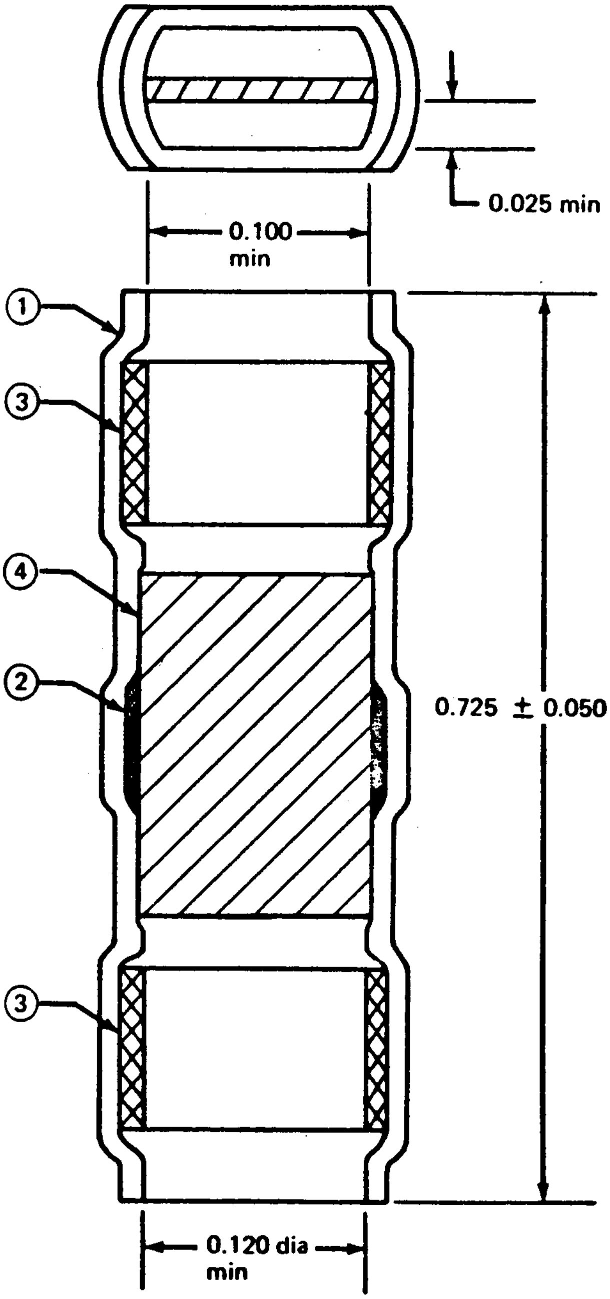


FIGURE 7 –SINGLE-CIRCUIT SPLICE

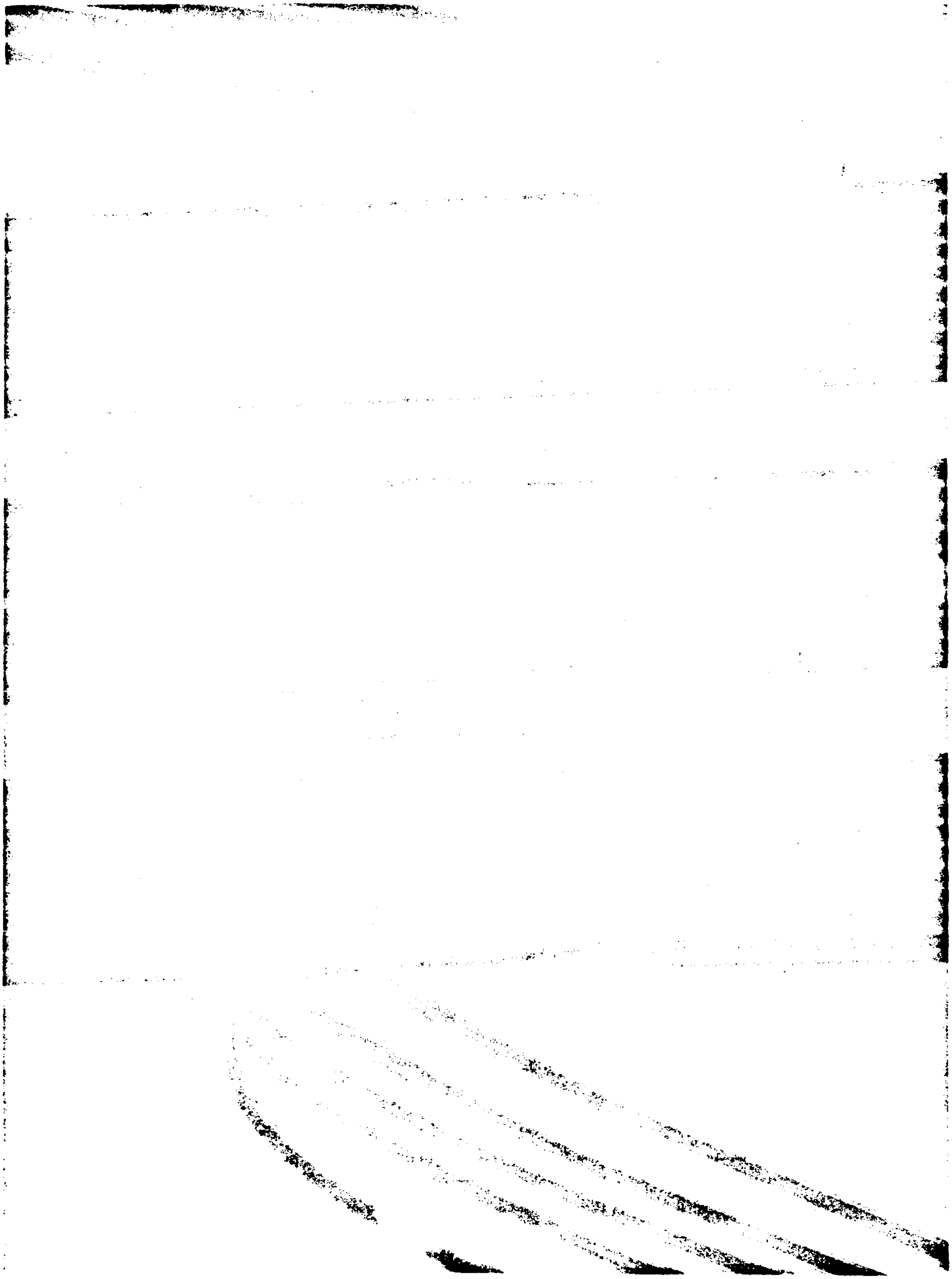


FIGURE 8 —SPLICE—BRANCH CIRCUIT TO FCC

TABLE 1 CRIMP CONCEPT PERMANENT SPLICE TERMINATION MVD CHANGE WITH ENVIRONMENT

Sample Code and Conductor Number	Splice Voltage Drop, mV						
	Initial Test	After Thermal Shock	After Thermal Aging	After Vibration[a]	After Moisture	After Salt Fog	Equal Lengths of FCC
B2-2	21.17	18.92	18.89		19.43	19.55	6.04
B2-3	13.27	13.40	13.50		13.56	13.48	6.04
B2-12	14.02		14.41		14.83	14.77	6.04
B2-13	14.16	14.19	14.41		14.43	14.43	6.04
B3-2	22.82	24.84	28.27		28.61	28.61	6.04
B3-3	15.75	15.94	16.09		16.10	16.00	6.04
B3-12	14.34	14.25	14.29		14.31	14.28	6.04
B3-13	14.[illegible]7	14.88	15.01		15.08	15.04	6.04
B4-2	12.90	13.11	13.20		13.20	13.22	6.04
B4-3	13.13	13.39	13.34		13.42	13.44	6.04
B4-12	14.11	14.17	14.11		14.17	14.15	6.04
B4-13	13.10	13.23	13.27		13.23	13.24	6.04

a Not required, accepted by similarity.

TABLE 2 —A-MP CRIMP CONCEPT PERMANENT SPLICE INSULATION RESISTANCE AND DIELECTRIC WITHSTAND VOLTAGE TEST DATA SUMMARY

Sample code[a]	Insulation resistance and dielectric withstand voltage					Failure details				
	Initial test	After thermal shock	After thermal aging	After moisture	After salt fog (final)	Failed conductors	Location (conductor no.)	Type	Voltage, min	Remarks
B1	OK	OK	N/R	N/R	N/R	None	–	–	–	
B2	OK	OK	OK	OK	OK	None	–	–	–	
B3	OK	OK	OK	OK	Fail	2	16, 17	Leak to adjacent	12	
B4	OK	OK	OK	OK	Fail	11	4, 5, 6, 7, 8, 9, 10, 12, 13, 18, 19	IR < 500 V	500	IR failure only
B5	OK	OK	OK	OK	Fail	2	12, 13	Leak to adjacent	10	May be due to MVD leads
B6	OK	OK	N/R	OK	Fail	10	2, 3, 6, 7, 8, 14, 15, 16, 17, 18	IR to adjacent	500	IR fail only
B7	OK	OK	OK	N/R	N/R	None	–	–		
B8	OK	OK	N/R	Fail	Fail	6	7, 8, 9, 10, 14, 15	Leak and IR to adjacent	10	
B9	Fail	Fail	N/R	N/R	N/R	2	10, 11	Leak to adjacent	10	
B10	OK	OK	N/R	N/R	N/R	None	–	–	–	
B21	OK	OK	N/R	N/R	N/R	None	–	–	–	
B22	OK	OK	OK	Fail	Fail	1	8	Leak to solution and IR to adjacent	10	
B23	OK	OK	OK	OK	OK	None	–	–	–	
B24	OK	OK	OK	OK	OK	2	12, 13	Shorts		Sensing leads shorted, otherwise OK
B25	OK	OK	Fail	Fail	Fail	17	All except 17, 18	Dielectric breakdown and IR	10	Mostly leak to solution and IR to adjacent
B26	OK	OK	N/R	OK	OK	None	–	–	–	
B27	OK	Fail	Fail	N/R	N/R	4	2, 3, 4, 5	Leak to adjacent	10	
B28	OK	OK	N/R	OK	OK	None	–	–	–	
B29	OK	OK	N/R	N/R	N/R	None	–	–	–	
B30	OK	OK	N/R	N/R	N/R	None	–	–	–	

[a]All samples were instrumented for MVD (2, 3, 12, and 13 monitored; 1, 4, 11, and 14 used as sensing leads).

TABLE 3 - MTSM CONCEPT PERMANENT SPLICE TERMINATION MVD CHANGE WITH ENVIRONMENT

Sample Code and Conductor Number	Splice Voltage Drop, mV						
	Initial Test	After Thermal Shock	After Thermal Aging	After Vibration[a]	After Moisture	After Salt Fog	Equal Lengths of FCC
A2-2	4.87	4.75	4.82		4.89	4.89	6.04
A2-3	4.78	4.66	4.69		4.67	4.65	6.04
A2-12	4.84	4.77	4.79		4.78	4.75	6.04
A2-13	4.86	4.76	4.80		4.78	4.77	6.04
A3-2	5.33	5.18	5.19		5.16	5.11	6.04
A3-3	5.11	5.02	5.04		5.04	4.99	6.04
A3-12	5.09	5.02	5.02		5.05	5.00	6.04
A3-13	4.98	4.91	4.93		4.92	4.88	6.04
A4-2	4.86	4.74	4.79		4.77	4.74	6.04
A4-3	4.91	4.86	4.83		4.79	4.80	6.04
A4-12	4.71	4.62	4.62		4.60	4.60	6.04
A4-13	4.64	4.58	4.59		4.61	4.56	6.04

a Not required; accepted by similarity.

TABLE 4 —MTSM CONCEPT PERMANENT SPLICE INSULATION RESISTANCE AND DIELECTRIC WITHSTAND VOLTAGE TEST DATA SUMMARY

Sample code	Insulation resistance and dielectric withstand voltage					Failure details				
	Initial test	After thermal shock	After thermal aging	After moisture	After salt fog (final)	Failed conductors	Location (conductor no.)	Type	Voltage, min	Remarks
A1	OK	N/R	N/R	N/R	OK	None	–	–	–	
[a]A2	OK	OK	OK	Fail	Fail	5	5, 6, 7, 8, 9	Breakdown to adjacent and solution	1500	
[a]A3	OK	OK	OK	Fail	Fail	2	6, 7	Breakdown to adjacent	10	Air bubble continuous 6-7; IR = 4.5 k ohm
[a]A4	OK	OK	OK	OK	OK	None	–	–	–	
A5	OK	OK	OK	Fail	Fail	7	1, 2, 3, 15, 16, 17, 18	Breakdown to adjacent and solution	700	Start of delamination between sealing material and outer jacket
A6	OK	N/R	N/R	OK	OK	None	–	–	–	
A7	OK	OK	OK	N/R	OK	None	–	–	–	
A8	OK	N/R	N/R	Fail	Fail	1	1	Breakdown to solution	12	
A9	OK	N/R	N/R	N/R	OK	None	–	–	–	
A10	OK	N/R	N/R	N/R	OK	None	–	–	–	
A21	OK	N/R	N/R	N/R	OK	None	–	–	–	
A22	OK	OK	OK	Fail	Fail	3	17, 18, 19	Breakdown to solution and adjacent	1500	Delamination 1/3 area of FCC side between sealing material and outer jacket
A23	OK	OK	OK	OK	OK	None	–	–	–	
A24	OK	OK	OK	OK	Fail	4	16, 17, 18, 19	Breakdown to solution	1500	
A25	OK	OK	OK	Fail	Fail	4	14, 15, 16, 17	Breakdown to solution	10	
A26	OK	N/R	N/R	OK	OK	None	–	–	–	Delamination 1/2 area of FCC side between sealing material and outer jacket
A27	OK	OK	OK	N/R	OK	None	–	–	–	
A28	OK	N/R	N/R	OK	OK	None	–	–	–	
A29	OK	N/R	N/R	N/R	OK	None	–	–	–	
A30	OK	N/R	N/R	N/R	OK	None	–	–	–	

[a]MVD instrumented

N/R = test not required per sequence.

Ultrasonic Welding Concept

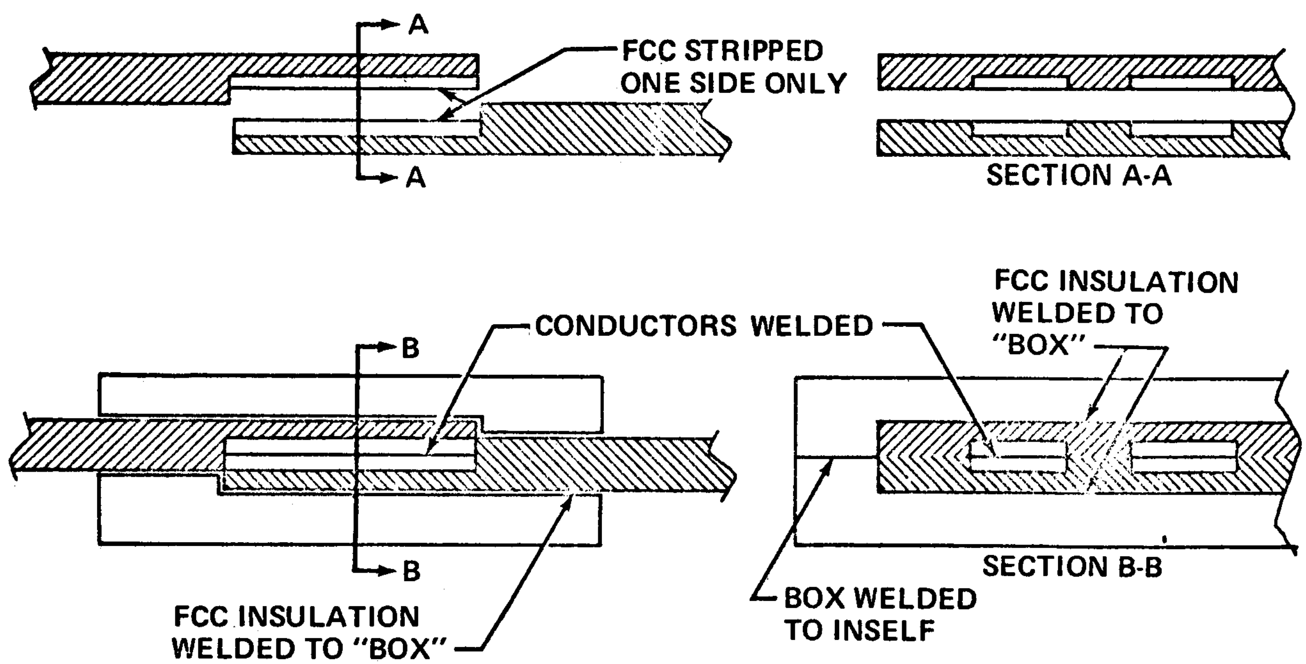


FIG 9

COST STUDY COMPARISON - FCC vs. RCC

by M. D'Almada Remedios
THE BOEING COMPANY
Commercial Airplane Group

INTRODUCTION

In any new technological development, progress is first directed at evaluating the technical aspects of the development. Prior to full exploitation, the economic impact of the development must be determined to assess penalty and payoff factors. The economics of the new technology must be studied and compared with current technology. However, a meaningful comparison must have the same basis. In this program the comparison was reduced to a comparison of costs per wire segment - any length of wire with two ends terminated.

A comparison was made between conventional round conductor cable (RCC) of AWG 20, 22, and 24 against flat conductor cable (FCC) and against AWG 30 small-gage wire (SGW). This was on a basis of 10 vehicles with each vehicle using approximately 100,000 feet of wiring and 2,000 connectors. The spread of wire size and connectors was based on a commercial airplane having similar quantities of wire and connectors. Due to the limited quantities per vehicle and the fleet size (10 vehicles) the cost of materials does not benefit from quantity procurement, and fabrication and installation costs do not benefit from learning curves.

This study was based on data from recent relevant R&D studies and from specific studies directed for the program. The data were amended to suit the vehicle parameters and updated to 1972 dollar values.

Basic Study

For the cost study, it was established that the wire size, function, and distribution of wiring in the vehicle would be similar to an equivalent-sized commercial airplane. Accordingly, an analysis of the wire sizes, lengths, and weights within several commercial

airplane models were evaluated. Results, tabulated hereunder, are considered to be applicable. It is evident that the three smaller gages (AWG 20, 22, and 24) predominate. Confining the study to these sizes will not introduce disproportionate errors.

Wire Size	Wire Length	Wire Weight (Lbs.)
1	74	5.16
2	264	73.92
4	341	55.47
6	220	24.84
8	713	51.34
10	923	40.13
12	1252	35.82
14	978	17.30
16	3911	47.68
18	5715	60.13
20	36105	289.88
22	44831	331.18
24	32233	97.50

WIRE SIZES, LENGTHS, AND WEIGHTS

Further, for small gage wire application, only size AWG 24 can be replaced with AWG 30; AWG 20 and 22 are current or voltage drop limited so they must remain unchanged.

In analyzing the cost of wiring for each operation, such as fabrication, assembly, and installation, it is desirable to relate all functions to some common denominator. For wiring, a wire segment (i.e., a single wire of any length terminated at both ends) is considered to be satisfactory. Therefore, the numbers of wire segments and wire bundles for the study vehicle have been determined, along

with the man-hours for conventional RCC materials and installations. The factors were evolved from production records.

WIRE DATA

WIRE SEGMENTS (average wire count)	18,500
NUMBER OF WIRE BUNDLES	330
NUMBER OF WIRES PER BUNDLE	56
MAN-HOURS REQUIRED	18,000
MAN-HOURS PER WIRE SEGMENT	0.97

In arriving at the figures, consideration was given to the total number of vehicles, in this case only 10. The man-hours per wire segment of 0.97 is high relative to production runs. Typically, average figures of 0.5, varying to as low as 0.2, are possible on production runs.

The cost involved in wiring is divided into the two functions, engineering and operations.

These are further subdivided:

- Engineering
  - Design
  - Electrical/electronic integration
  - Cable assembly drawings
  - Installation
  - Electronic data processing - wiring

- o Operations

  Mockup

  Tooling and production planning

  Fabrication

  Assembly

  Installation

  Quality Control

The proportion of the cost of one function (engineering) over the other (operations) varies considerably from the first vehicle to the nth vehicle, as would the actual cost. For example, initially engineering would be as high as 50% of the high initial cost, but, by the nth vehicle, the engineering share would be a small portion of the low final cost. Therefore, it was considered realistic for this program to apportion the costs on a basis of engineering 33.3% and operations 66.7% of the total cost.

In arriving at a cost per wire segment, consideration was given to the special nature of the vehicle, the reliability requirements, and other stringent factors as well as to the limited production. The figure of $10 per segment selected compares with figures for production runs that typically range from $7 per segment to $2 per segment.

COST BREAKDOWN BY FUNCTIONS

FUNCTION	COST PER SEGMENT $	
Engineering	3.33	
Operations	6.670	
Mockup		1.32
Tooling and production planning		0.202
Fabrication and assembly		3.748
Installation		1.400
Total	10.00	

COST COMPARISON

To compare the various configurations against the basic conventional round wire system, it was necessary to be able to directly compare each configuration, function by function. It was at first considered practical to select typical bundles and establish cost variation factors for each using RCC, SGW, FCC, and their variations. Typical bundles representing a long run, a medium run, and a short run were selected. This approach was determined as being too involved and no more accurate than comparing a single bundle for each of the configurations (RCC, SGW, FCC, and their variations).

Accordingly, standard RCC wire bundle 10 feet long and consisting of 55 wires branching into two circuits of 33 wires and 22 wires, respectively, was selected as the basis for comparison. The standard bundle, two SGW bundles, and an FCC bundle, all with the same wire count, are illustrated per attached sketches. The four configurations shown, along with four others, were evaluated for costs of engineering, operations, and materials. The eight configurations are as follows:

1) Standard RCC — This represents the basic or standard RCC bundle on which the cost rates were established

2) SGW-1 — This is a small-gage wire bundle with braided jacket and stress relief tensile member.

3) SGW-2 This small gage wire bundle has a braided jacket transitioned to a convoluted-tubing jacket for the last 8 inches of the bundle run.

4) FCC-TS-1 This is a FCC bundle with transition splices (TS) to RCC so as to enable conventional RCC connectors to be used. The TS will be the same as configuration 1 developed in Phase I of this program.

5) FCC-TS-2 This is similar to configuration 4 above, but the splice joints are welded.

6) FCC-TS-3 The transition splice in this case is per configuration 3 (MTSM) developed in Phase I of this program.

7) FCC-D-1 This is a FCC installation directly terminated in FCC connectors. The connectors are the crimp-through insulation type (A-MP Unyt) as installed in the 727-100 mockup installation.

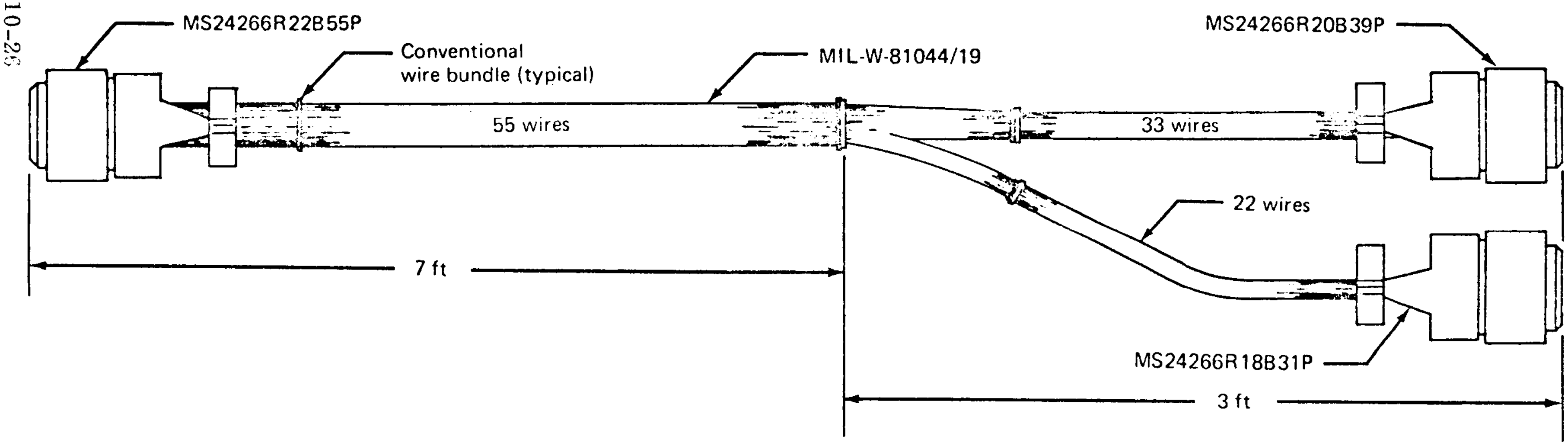
8) FCC-D-2 This is similar to configuration 7 above, but in this case a three-wafer Cannon connector with welded terminations and potted connector grommet is used.

Engineering and Operations Labor Cost Summary

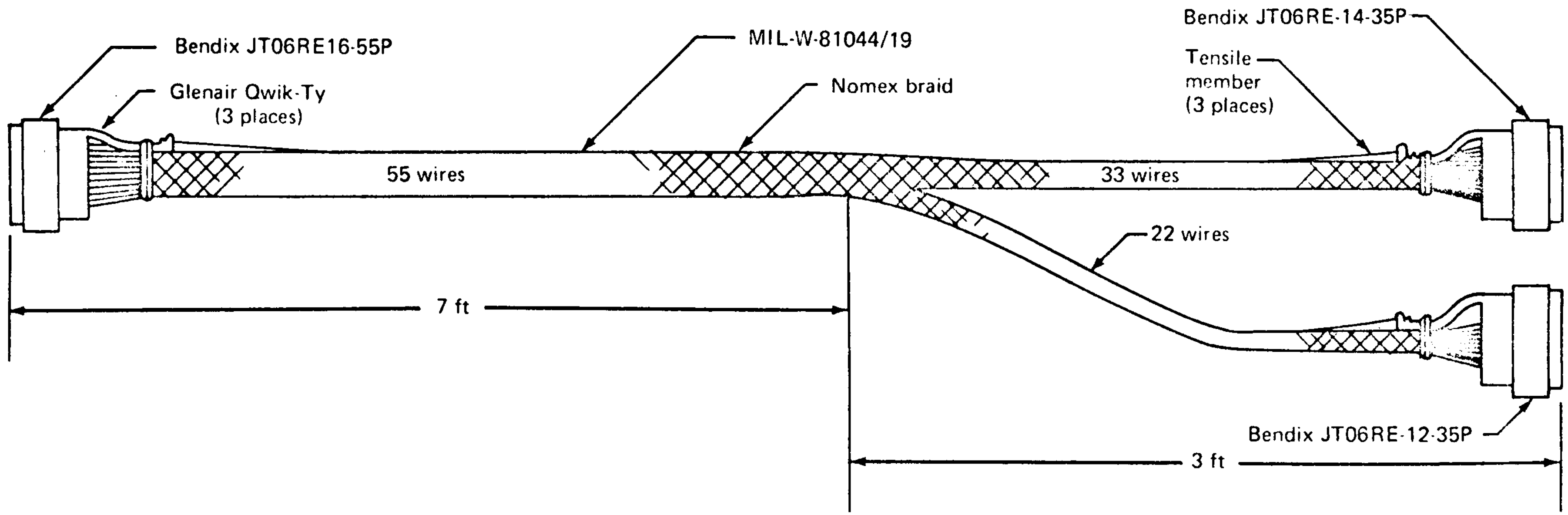
The engineering and operations evaluation emphasis that engineering and fabrication and assembly are two functions that consume a large proportion of the total cost. Where these functions can be simplified, very significant cost savings are achieved. This is clearly evident in the following chart which summarizes the evaluation.

COST COMPARISON SUMMARY - ENGINEERING AND OPERATIONS

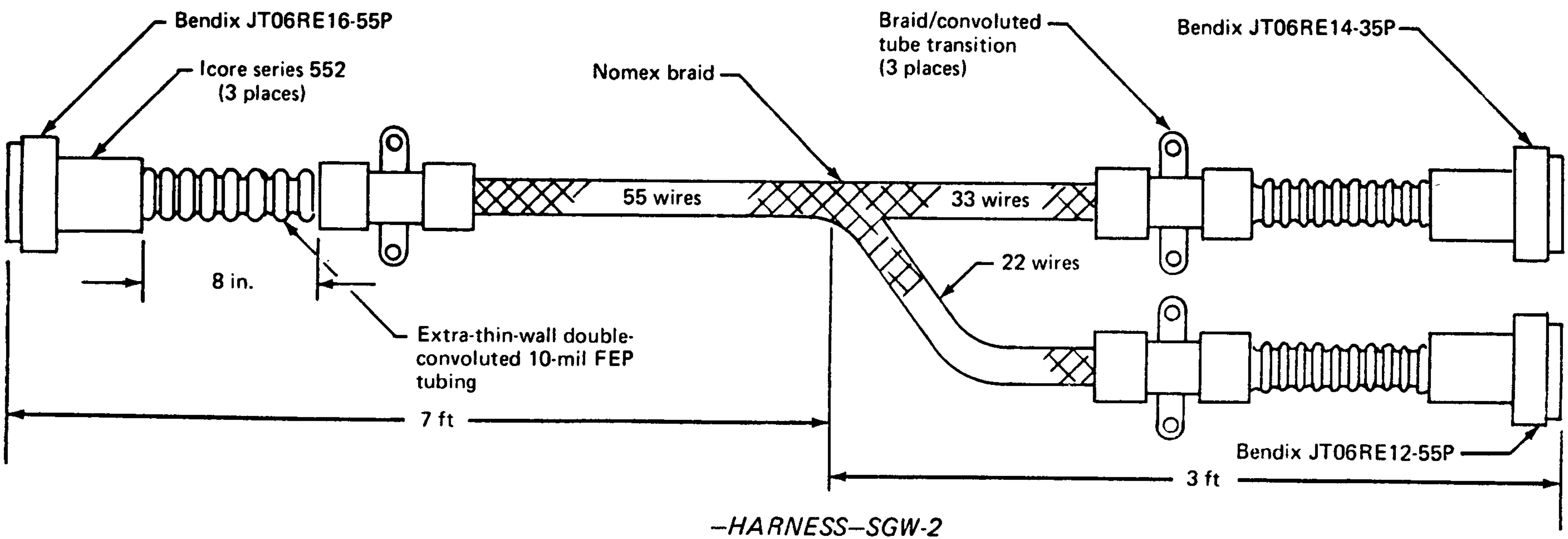
FUNCTION	CONFIGURATION							
	1	2	3	4	5	6	7	8
	Cost Per Segment,$							
Engineering	3.33	3.60	3.60	3.60	3.50	3.50	3.40	3.40
Operations								
Mockup	1.32	1.40	1.55	1.10	1.10	1.00	1.00	1.00
Tooling & Production Planning	0.202	0.30	0.35	0.16	0.18	0.17	0.15	0.16
Fabrication & Assy.	3.748	4.10	4.88	3.06	2.43	3.42	0.326	1.14
Installation	1.40	1.60	1.60	1.00	1.00	1.00	0.70	0.70
TOTAL	10.00	11.00	11.98	8.92	8.21	9.19	5.556	6.40



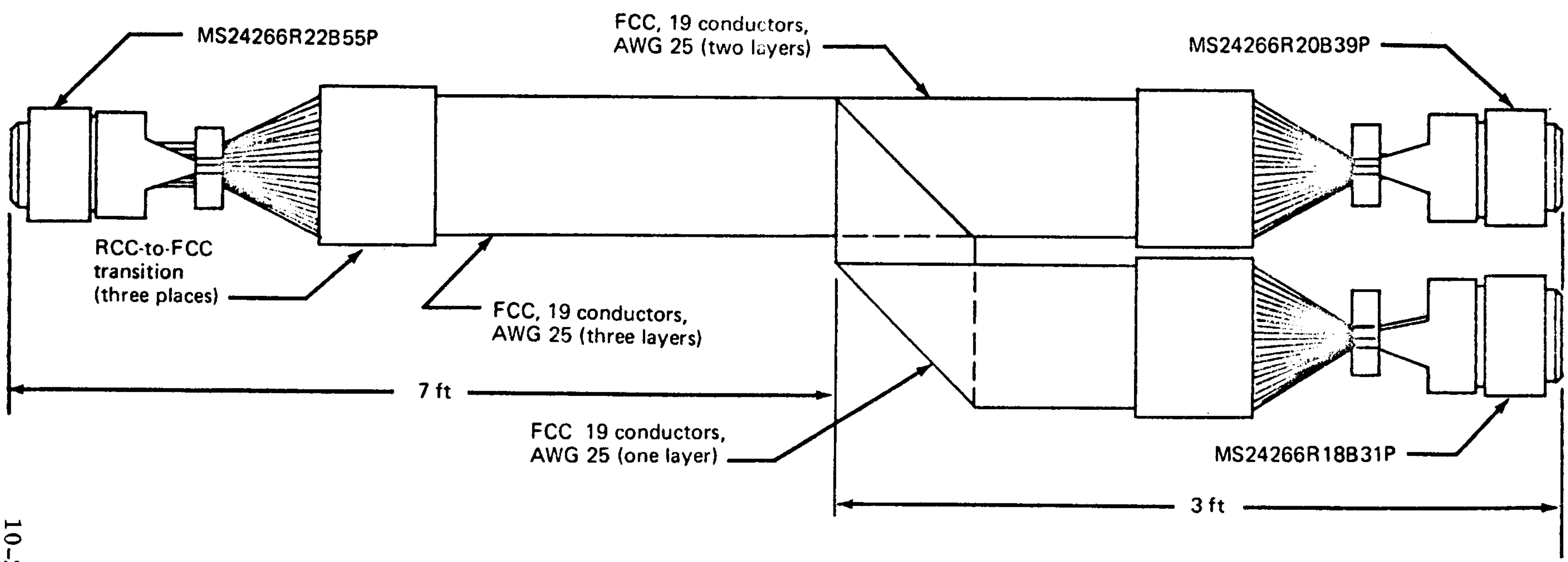
—STANDARD RCC WIRE BUNDLE



—HARNESS—SGW-1



–HARNESS–SGW-2



–HARNESS FCC-TS-1

MATERIAL COST EVALUATION

The approach taken for material cost evaluation was to (a) derive a basic material average cost per segment for standard RCC wiring of a complete commercial vehicle that is similar in size to the space shuttle, (b) establish a correction factor by analyzing itemized costs of materials for a specific typical bundle design for all the new technology configurations andcomparing them with the costs of the standard configuration of the same bundle design, and (c) project a cost per segment for each new technology configuration by taking the basic cost per segment for standard RCC from (a) and multiplying by the correction factor established in (b).

Basic Costs

One method of deriving basic costs of standard RCC wiring for a similar-sized vehicle is to use actual production cost figures. These costs were normally separated into specialized costs (developmental, tooling, etc.) and production parts costs. The data available varied with the size of the production run, but the following are typical:

Special Costs	
Developmental (related to materials only)	\$ 9,000.00
Tooling (special production tooling)	\$ 2,000.00
Purchased equipment (special for the project only)	\$ 5,000.00
Total special costs	\$16,000.00
Production part costs	\$48,000.00

Another method of arriving at a total material cost figure is to itemize costs based on 127,500 feet of wire and 2000 connectors. Approximately 110,000 feet of the wire consisted of AWG 20,22,and 24, which, for BMS 13-42 (MIL-W-81044), would have an average cost of \$62.50/1000 ft or a total of \$6,875. The balance of the wire would be larger sizes and specials, i.e., 20,000 ft at \$150.00/1000 ft for a total of \$3000. For 2000 connectors (MIL-C-26500), at

\$22 per mated pair, the cost would be \$44,000. Thus, the total for production parts would be \$53,875.

The above two material cost totals for production parts can now be averaged to (48,000 + 53,875)/2 = \$50,937. Add total special costs of \$16,000 to give total material costs for standard wire per vehicle of \$66,937. Then, for 18,500 wire segments, the total material cost per segment is

$$\frac{\$66,937}{18,500} = \$3.618 \text{ per segment}$$

This established the costs for standard RCC wiring on a complete vehicle as

Real material cost	\$66,937
Real cost per segment	\$ 3.618

Configuration Correction Factor Analysis

Eight configurations were defined at the beginning of the cost comparison discussion. These configurations were analyzed on the basis of material cost to establish correction factors to be used in deriving new technology configuration real costs.

Because materials are affected by bundle or segment length, all configurations were compared for lengths of 5, 10, 30, and 75 ft to obtain a measure of cost variation. The following tabulates the results for each configuration. The cost per average segment is also shown. (The average segment length was 6.9 ft, based on 18,500 segments and 127,500 ft. of wire.)

MATERIAL COST SUMMARY

ITEM	CONFIGURATION							
	1	2	3	4	5	6	7	8
Cost per average segment	\$1.29	\$3.76	\$4.85	\$1.60	\$1.75	\$1.73	\$3.87	\$5.52
Fixed cost per segment	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Total cost per average segment	2.16	4.63	5.72	2.47	2.62	2.60	4.74	6.39
Correction factor $= \frac{\text{configuration n}}{\text{configuration I}}$	1	2.14	2.65	1.14	1.22	1.20	2.19	2.96
"Real" cost per segment	\$3.618	\$7.74	\$9.59	\$4.12	\$4.41	\$4.34	\$7.92	\$10.71

The above analysis provides the total cost per average segment for both standard RCC and the new technology configurations. The correction factor is then derived by comparing each new technology configuration with the standard RCC configuration.

Configuration "real" cost per segment was calculated by applying its correction factor to the "real" cost per segment for standard RCC wiring ($3.618 established previously). For example, for configuration 2, "real" cost per segment = 2.14 x 3.618 = $7.74.

TOTAL COST SUMMARY

The engineering and operations analysis resulted in labor costs per segment for each of the eight configurations. The materials analysis produced the "real" material cost per segment. The following projects the total cost per segment (labor plus materials).

TOTAL COST SUMMARY

ITEM	CONFIGURATION							
	1	2	3	4	5	6	7	8
Labor cost per segment	$10.00	11.00	11.98	8.92	18.21	9.19	5.56	6.40
Material cost per segment	3.618	7.74	9.59	4.12	4.41	4.34	7.92	10.70
Total cost per segment	$13.618	18.74	21.57	13.04	12.62	13.53	13.48	17.10

WEIGHT/COST EVALUATION

Weight analyses were performed for each of the eight bundle configurations as well as for the total vehicle. These analyses assume the following special factors.

- o The study was limited to 110,000 ft of wire, which represented the conventional application of AWG 20, 22 and 24 only, and considered an equal division between these gages.
- o In all cases, the connector weights were doubled to represent mated pairs.

- Connector population perbundle was adjusted from the three mated pairs used in the sample bundle to 10 mated pairs to result in a total vehicle connector cound of 2000 mated pairs.
- For configurations 2 and 3, conventional wire was used for AWG 20 and 22 applications andonly the AWG 24 wire was replaced with SGW.
- In the case of FCC applications, some liberties were taken with gage sizes as listed below:

Conventional Wire Size, AWG	FCC Wire Size, AWG
20	21
22	25
24	28

- For the total vehicle wire weight, 200 wire bundles per configuration, each 10 ft long and having 55 circuits, were considered.

Data from previous analyses were projected for manufacturing wiring cost per vehicle, weight per vehicle, and operation cost per vehicle based on 10 missions and total value of technology for the various harness configurations. The following factors were used in this cost study:

- Usage factors and gage size restrictions similar to those used in the weight analysis were imposed.
- All gages of FCC (21, 25, and 28) and their associated connectors were considered of equal cost.
- Costs were reduced for both unsealed and sealed FCC connectors from those quoted by manufacturers to account for production implementation.

The tabulation hereunder projects the wiring cost per vehicle based on AWG 20, 22, and 24 wire usage.

VEHICLE MANUFACTURING WIRING COST DATA - DETAILS[a]

Config-uration	Labor cost per segment, $	Materials cost per segment, $	total cost per segment, $	Number of segments	Total cost per vehicle, $
1	10.00	3.61	13.618	16,000	217,904.00
[b]2	11.00	7.74	13.618	10,066	145,260.25
			18.74	5,334	99,959.16
					245,219.41
[b]3	11.98	9.59	13.618	10,669	145,260.25
			21.57	5,334	115,054.38
					260,314.63
4	8.92	4.12	13.04	16,000	208,640.00
5	8.21	4.41	12.62	16,000	201,920.00
6	9.19	4.34	13.53	16,000	216,480.00
7	5.556	7.92	13.48	16,000	215,680.00
8	6.40	10.71	17.10	16,000	273,760.00

a Total vehicle wire length is 127,500 ft.
There are 18,500 segments per vehicle or an average of 6.9 ft. per segment
Of the 18,500 segments, 16,000 are of AWG 20,22, and 24 wire with a total length of 110,000 ft.

b Conventional wiring used with SGW as follows: 10,666 segments of AWG 20 and 22; 5,334 segments of AWG 30.

To arrive at the optimum choice of harness configuration for application to a vehicle such as the space shuttle, the total value of technology was considered as the figure of merit desired. Total value of technology is defined as th total of wiring manufacturing costs per vehicle plus the cost impact of vehicle weight on payload per mission multiplied by ten missions. The mission cost is to be based on the cumulative average mission cost over the program life of 15 years.

Space shuttle program cost impact of vehicle weight on payload per mission, based on data from the NASA planning estimate for the 15 year space shuttle effort dated March 1972, are as follows:

Total budget through first flight (1978)	$\$5.5 \times 10^9$
Follow-on 10 year program costs covering additional vehicles and 450 flights	$\$2.0 \times 10^9$
Nominal space shuttle payload - each way	40,000 lb

The average cost per flight over 15 years and 451 flights is $16.67 million per flight. This resolves to a cost per pound of payload per flight of $416.8 over the 15 year period. From this, the cost impact on payload equals delta weight - times **$416.8**, e.g. for configuration 2, cost impact on payload equals - 143.67 X 416.8 = 598,817 and by definition total value of technology equals - 598,817 + 245 219 = $ 353,598.

The total value of wiring technology applied to the space shuttle program, as described above, is tabulated.

TOTAL VALUE OF VEHICLE WIRING TECHNOLOGY - SUMMARY

Configuration	Vehicle wiring manufacturing cost [a]		Vehicle wiring weight[a], lb		Cost impact on payload[b]	Total Value of Technology[c]
	Total	Delta	Total	Delta		
1	$217,904	Ref	868.40	ref	$ -	$+217,904
2	245,219-	$ +27,315	724.73	-143.67	-598,817	-353,598
3	260,315	+42,411	753.73	-114.67	-477,944	-217,630
4	208,640-	- 9,264	762.88	-105.52	-439,807	-231,167
5	201,920-	-15,984	762.88	-105.52	-439.807	-237,887
6	216,480	- 1,424	738.88	-129.52	-539.839	-323,359
7	215,680	- 2,224	745.70	-122.70	-511,414	-295,734
8	273,760	+55,856	591.30	-277.10	-1,154,952	-881,192

a Vehicle wiring manufacturing costs and weight totals are limited to 110,000 ft. of conventional RCC and do not include "other" types such as larger gages (power circuits), coaxial cables, engine circuits, fire detection wiring, etc.

b Based on $416.8/lb of payload and 10 flights per vehicle.

c(+) indicates program cost based on base payload delivered and
(-) indicates cost benefits due to added payload capacity through first 10 flights per vehicle.

In analyzing the previous data, it is apparent that the optimum total value of wiring technology for the space shuttle would be achieved if a hybrid of the various wiring harness. For example, a combination of configuration 2 and configuration 8 would give a weight saving of 326.9 lbs as follows:

WIRING WEIGHT - HYBRID SYSTEM

Configuration	Wire Size, AWG	Weight, Lb.
8	21 (FCC)	247.1
8	25 (FCC)	189.9
2	30 (SGW)	104.5
	Total	541.5

868.4 lb (conventional wire weight)
541.5 lb (new technology wire weight)

326.9 lb weight saving

MANUFACTURING COSTS - HYBRID SYSTEM

Configuration	Conventional wire size, AWG	Wire Segments	New Technology Wire size, AWG	Cost per Segment	Total Cost
8	20	5,333	21 (FCC)	$17.10	$ 91,194.30
8	22	5,333	25 (FCC)	27.10	91,194.30
2	24	5,334	30 (SGW)	18.74	99,959.16
	Total	16,000		$17.60 (average)	$282,347.76

and Cost Impact on payload for the hybrid system

= weight saved X payload cost X number of flights

= 326.9 X 416.8 X 10

= 1,362,561.

Total Value of Technology = Manufacturing Cost - Cost Impact

= $282,377 - 1,362,561

= $ - 1,080, 184.

Conclusions

It was concluded that any new technology wiring within the seven configurations considered will result in a benefit to the total value of technology. Application of these wiring technologies to future air and space vehicles having a cost-impact-of-weight-on-payload factor of $300/lb and above is mandatory. In fact, even with the significant material cost disadvantages for the new technologies, the total results indicate large gains by their application.

o Engineering Costs - Engineering costs are $3.33 out of a total of $13.618 per segment for conventional RCC wiring (24.5% of the total vehicle manufacturing wiring costs). Detailed cost impact studies are needed to determine sensitivity of engineering cost per segment versus various wiring technologies.

o Fabrication and Assembly Costs - These costs for conventional wiring are 27.5% of the total costs per segment. Detailed analyses, including industrial engineering time and motion studies, should be conducted to establish more accurate costs for the new wiring technologies.

- Material Costs - The material costs per segment vary from 26.5% for conventional wiring to the range of 44%-67% for some of the new technology wiring. These material costs are excessive. However, they are based on prices that have been reduced a significant amount, arbitrarily, from prices quoted by the suppliers. It has been noted that industry cost reductions have been significant in other areas (standard wire, connectors, microelectronics, etc.) as standards are established and widespread usage occurs.

In conclusion it is suggested that a realistic approach be taken to standardize and drive up the usage and drive down the cost and keep the snow ball rolling.

DEVELOPMENT OF A FLAT CABLE SYSTEM

By Robert M. Neel
Raychem Corp.

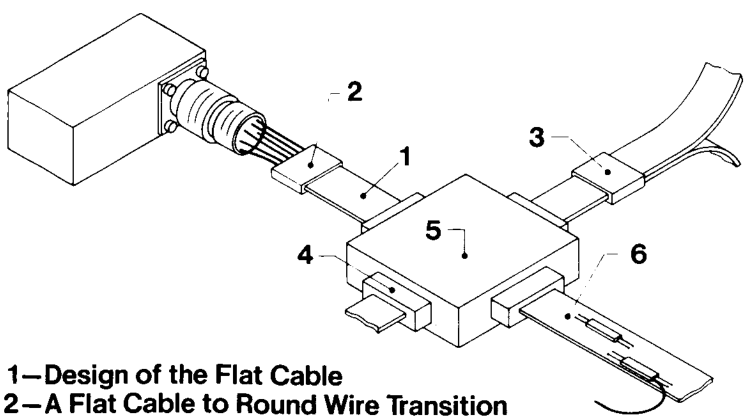
SUMMARY

Raychem is currently developing a flat conductor cabling system for electrical/electronic interwiring. Six major items comprise the system: the cable, splices—one for flat cable to round wires and one for flat cable to flat cable; a series of flat cable connectors; the distributor, which is used for interconnecting the circuits; and a repair technique for the flat cable. Several totally new and innovative developments contribute to the uniqueness of this flat cable system. Polyarylene, Raychem's new high performance melt-processable insulation material, permits the design of a completely different, completely standardized, modular flat conductor flat cable. The development of an advanced heat-shrinkable plastics technology involving the use of selectively bonded plastic film has resulted in the Multiple Termination Module, or MTM, used for making high-reliability sealed solder terminations to either flat conductor cable or round wires. All necessary tools and application equipment are also part of the development program. With its versatility, gained by a workable standardization of sizes, and its total compatibility of both materials and design, this new system overcomes most of the problems which have prevented flat cable from gaining wide acceptance and usage.

THE SYSTEMS APPROACH TO FLAT CABLE

The increasing complexity and miniaturization of electronic systems is pushing conventional round wiring to and beyond the limit of its practicality. Several studies have indicated that a change to multiply-terminated flat-configuration-wiring will lower installed costs, reduce or simplify maintenance, and potentially increase overall system reliability. In early summer, 1971, Raychem began a program to develop a flat cable wiring system. Initially, the project was to look at the problems with present flat cable and flat cable systems, assess why flat cable has not been more widely used, and determine what could be done by way of new concepts and new approaches to eliminate the problem areas. One of the immediate conclusions as to why flat cable had not been readily accepted was that most suppliers were basically working on small parts of the overall problem, forcing the user to integrate the entire system. Termination methods were not designed to be compatible with the cable, most materials were equally incompatible, and flat cable standards were so profuse and all-inclusive that they did nothing toward bringing about real standardization of flat cable. Thus, the most important initial step was to outline the existing major problem areas so that development could progress toward a total solution rather than solving mere segments.

Six major problems with flat cable wiring were defined: (Figure 1)



1—Design of the Flat Cable
2—A Flat Cable to Round Wire Transition
3—A Flat-to-Flat Splice
4—A Flat Cable Connector
5—The Distributor or Junction Box
6—Repair or Modification of the Flat Cable

Figure 1

A mere composite of the answers to these problem areas does not represent a total solution. All segments must be totally committed to compatibility with the whole system. Furthermore, all procedures and necessary tooling and equipment must be developed as an integral part of the implementation of the system. It is Raychem's contention that a fully integrated "systems approach" to flat cable wiring is the only way to achieve a workable, versatile and acceptable solution.

Standardization

What might be considered a seventh, but less technical, "problem area" is that of standardization. Or lack of it...

There are currently over 1,300 "standard" flat conductor flat cable (FCC) configurations specified in MIL-C-55543, NAS 729, and IPC-FC-220. The best of these (NAS 729) calls out 66; MIL-C-55543 has 1,134! This tremendous proliferation of sizes and types makes most cable manufacturers apprehensive—with good reason—about getting into the FCC business. It makes designers and manufacturers even more frustrated to be required to have a different cable, connector, and splice for every configuration. To handle all the variations, equipment changes would be constant and short runs of a lot of different sizes will never be economically attractive. Set up charges alone have precluded the use of flat cable in anything other than very large volume. Inventory, tooling and stocking requirements become tremendously costly. Because of the multi-conductor nature of FCC, it is essential to have long runs of as few sizes as possible to make the cable truly cost-competitive with round wire. Thus, until real, workable standards are chosen, FCC will never reach the price level at which it can achieve its greatest cost-saving potential.

Standardization alone is not the answer. Many systems have been known to die from being slaved to unrealistic, unworkable standards.

The key, therefore, is to achieve greater versatility and greater simplification through the selection of good standards. The first requisite for good standardization is to supply a versatile approach that provides the designer the same wiring capability now available. FCC can not survive on its novelty—reduced termination costs and higher reliability through multiple termination are the only way it will become a really viable product. These can only be accomplished by the adoption of highly versatile, greatly simplified and very thorough standards for both the cable and terminating devices. Raychem is proposing such a standard.

DESIGN OF THE FLAT CABLE

With all the different specified configurations, none has been designed specifically to be compatible with a given termination process. Nor has any concern been given to how it is to be sealed, repaired, or adapted to the entire system. Generally, electrical characteristics of the cable and producibility are the prime concerns, rather than the more demanding problem of how it is to interface with connectors, splices, black boxes and other hardware. Very often, cables which are very difficult if not impossible to strip are used in situations where the conductor must be bared for termination.

Raychem has developed an extruded, modular-width, strippable, standardized flat cable that is completely compatible with the new multiple solder termination technique and all other parts of the flat cable system. The standardization (see Table 1) consists of only three center spacings, three cable widths, and one conductor size per spacing. For maximum utility, each spacing has the largest conductor that can be reasonably accommodated. Only eight different cables are proposed, contrasted to tens to hundreds of cables in other standards.

TABLE 1. FLAT CABLE STANDARDIZATION

Conductor Spacing	Cable Widths			Conductor Size	Equiv. AWG Wire Size
	1/2"	1"	2"		
	Number of Conductors				
.050	10	20	40	.005 x .025	28
.100	5	10	20	.005 x .065	24
.200	--	5	10	.008 x .160	18

Polyarylene, Raychem's new cable insulating material, makes it possible to extrude very high performance flat cable having a full width of conductors, contrasted to laminated designs which waste space on the edges (see Figure 2). This seemingly subtle difference (A versus A') is actually what makes the design completely modular. Cables can be layed side-by-side without disrupting conductor center spacing. Since the standard sizes "double" (width and number of conductors) as they increase, smaller cables can be combined modularly and used in place of one larger cable. The need for many cable configurations would be met by the ability to combine cables - "mix and match" - but still terminate to completely standard splices and connectors. Further, the volume usage of only eight different sizes would increase cable reliability and ultimately reduce the price.

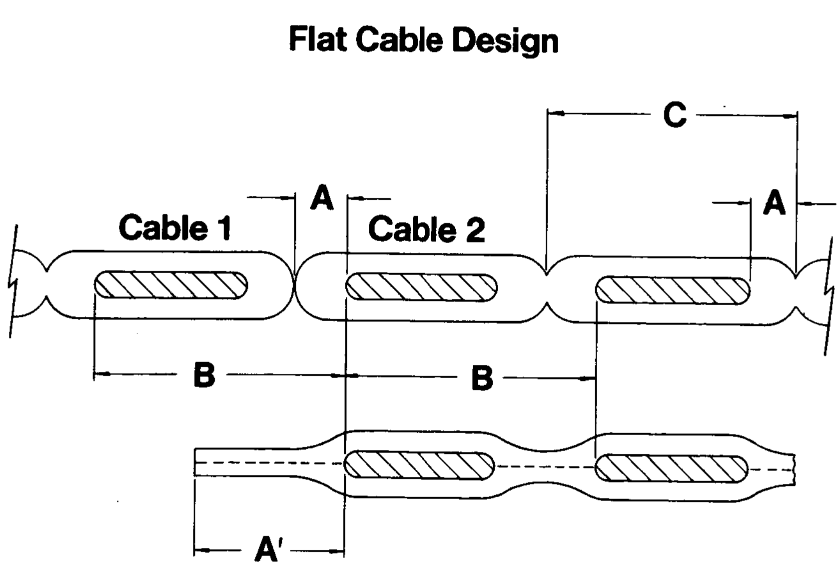


Figure 2

The insulation is designed to be easily removed, either by a cold blade stripper such as the NASA design, or more simply by a matched-die mechanical stripper shown schematically below. Raychem is currently developing such a stripper, which also provides the capability of quarter-stripping flat conductor flat cable.

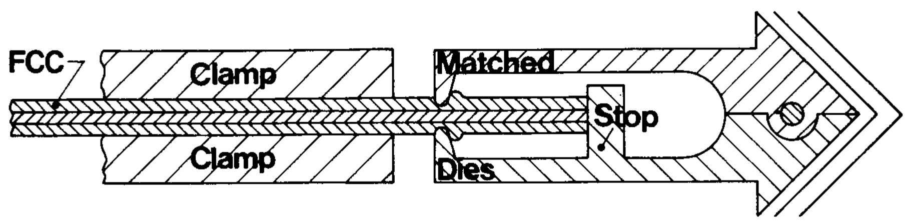


Figure 3. Schematic representation of matched-die flat cable stripper.

This ease of stripping is a natural compliment to the reliability and adaptability of a multiple solder termination process. It results from the fact that the insulation is extruded onto the conductor under very controlled process conditions so that the amount of adhesion to the conductor can be closely controlled. The most reliable and consistent means for terminating to flat conductors is achieved by removing the insulation, and therefore good stripability is essential for high quality multiple flat cable terminations.

Another feature of the extruded design is the tear-groove between each conductor. With this, a single conductor can be stripped out of the cable (repair, breakouts, jumpering, etc.) without jeopardizing the overall mechanical integrity. Each conductor is fully insulated and will perform as well individually as it does in the total cable. "Tree"-type harnessing is now possible with flat conductor cable (Figure 4), combining the advantages of flat cable with those of round wire systems. This "stripping-down" of the cable, together with the modular "building-up" of cables, provides the designer complete versatility in a flat cable system.

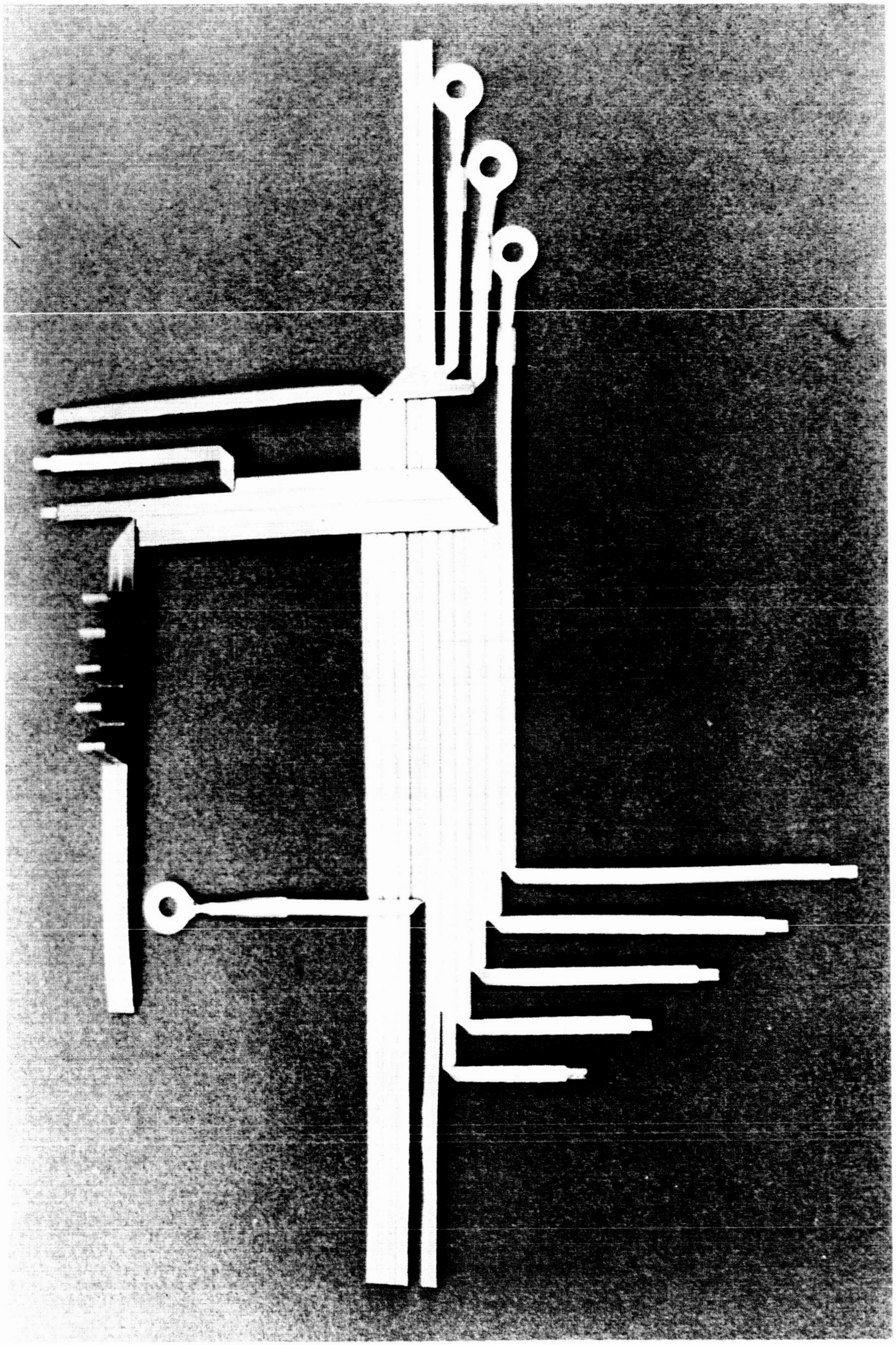


Figure 4. "Tree"-type harnessing with FCC.

A FLAT CABLE TO ROUND WIRE TRANSITION

In no way will flat cable completely replace round wire systems; each has its place. Flat cable will always have to interface with round wires, since standard round or rectangular round-wire connectors are and will continue to be used on black box equipment. A highly reliable flat-to-round splice will answer two major needs: 1) using standard connectors in a flat cable system to maintain interchangeability with existing equipment and to fill the gap until reliable flat cable connectors become more universally available; 2) using round wire in those standard connectors as they were originally designed. To meet the requirements for system compatibility, low installed cost, environmental protection, high reliability, small size, light weight, and simplified application, Raychem has employed a termination concept similar to that of the known and proven heat shrinkable Solder Sleeve™. Flat cable, however, required the development of several innovations in the termination configuration. Primarily, the heat-shrinkable insulating member is not tubular, but rather is fabricated from two layers of plastic film which are selectively bonded together. To better understand the differences, it is well to review how heat recoverable tubing is manufactured and how its properties are used in conventional Solder Sleeve™ devices.

Plastic tubing is first extruded in its desired final size, then irradiated by electron beam to effect a cross-linking of the plastic's molecular chains. The cross-linked material will no longer melt and flow but now behaves as an elastomer at temperatures above its crystalline melting point (hence, its "memory"). To expand the tubing, it is heated and mechanically enlarged, then cooled while held at the expanded size. This stores mechanical energy in the tubing. When re-heated above the crystalline melting point, the energy is released and the tubing will recover, or "shrink" to its original extruded diameter, if not restricted. (Figure 5).

The Solder Sleeve™ is made by placing a pre-fluxed solder ring and meltable sealing rings in the expanded tubing, then locking them in place by partially recovering the tubing around them (Figure 6). To use the part, wires are positioned inside and heat is applied. The sealing rings melt as the outer sleeve shrinks, and after the flux has flowed and the part has reached soldering temperature, the mechanical energy stored in the expanded tubing serves to force the solder into the joint area. The result is an insulated, encapsulated and inspectable solder termination from a single operation.

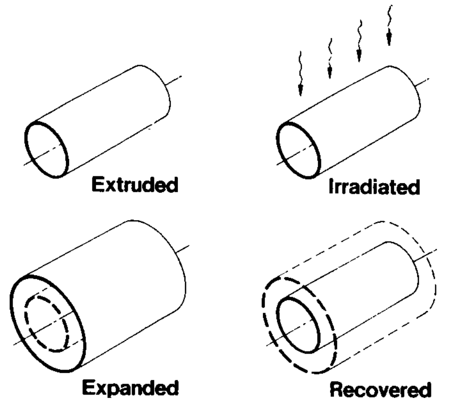


Figure 5

Since Solder Sleeves™ are round, they are not suited to flat cable terminations. The bonded-film process was developed to overcome this configuration problem. In this process, two sheets of closely controlled plastic film are selectively bonded together in a pre-determined spacing pattern (Figure 7). The material is then irradiation cross-linked and expanded under a controlled process. This process only allows the part to expand perpendicular to the plane of the film and the bonding pattern is held fixed, yielding accurate centers spacing and part geometry. When heated the part recovers completely <u>flat</u> with no change in bonding pattern.

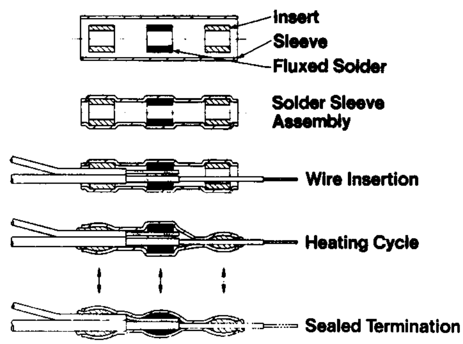


Figure 6

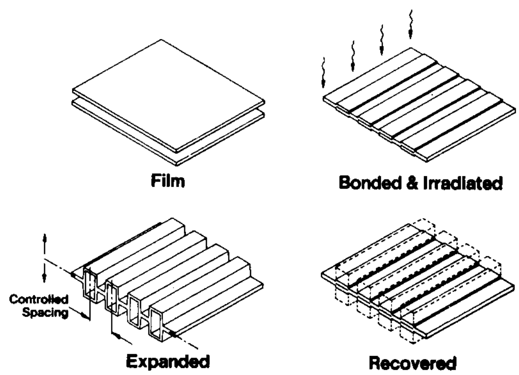


Figure 7

The bonded-film process is the key to the MTSM, or Multiple Termination Splice Module. The MTSM incorporates the proven Solder Sleeve™ termination concept in each compartment of a bonded-film insulating member. The part for splicing flat cable to round wires has a series of compartments to accommodate each individual conductor, and a boot section on one end for the flat cable insulation (Figure 8). Fluxed, solder-coated metallic connecting strips are located in each termination compartment. They are formed to match the conductor shape with a flat end for flat conductors and a cupped section for round wires (Figure 9). When the splice is terminated, each conductor is re-flow soldered to the metallic support strip which serves to strengthen the joint (Figure 10).

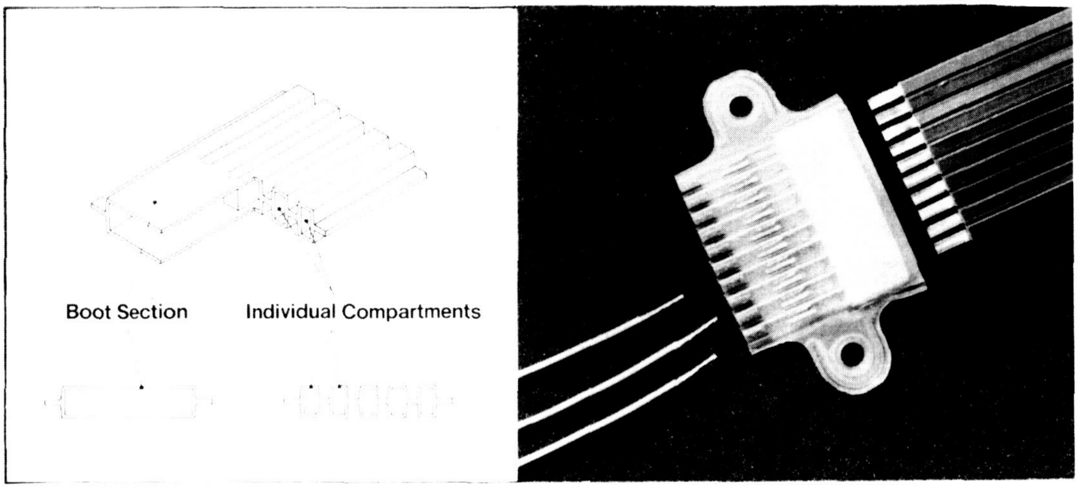


Figure 8

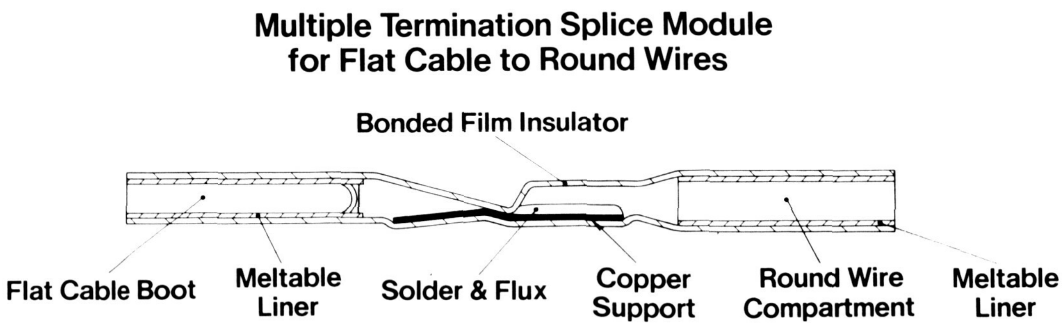


Figure 10. Cross-sections of the MTSM soldered terminations.

Any splice has to be at least as good mechanically and electrically as an equivalent length of unspliced cable. With flat conductor cable this is very difficult since the conductors are locked closely together and each conductor must be sealed and insulated from its neighbor. To seal up the critical close-spaced area between conductors, the MTSM has a specially designed adhesive part, shaped like a finger-less glove, in the flat cable boot section (Figure 11). When the stripped cable is inserted, the bared conductors protrude through the fingerholes into each individual compartment. The material is then in position to form a bond to the cable insulation and to the MTSM, completely sealing and encapsulating each conductor at the strip point. Another meltable ring is used to seal the round wire end so each termination compartment is completely insulated, sealed and strain relieved. The result is a splice that is mechanically and electrically better than unspliced cable, as evidenced by a much higher breaking strength and a lower millivolt drop.

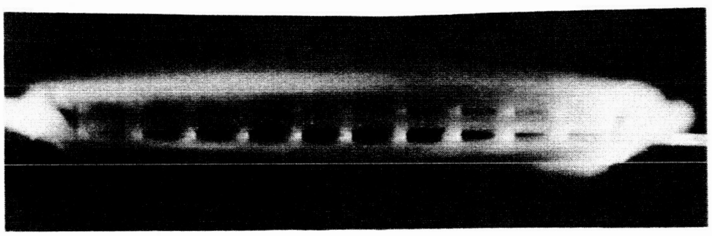


Figure 11.

To splice flat cable to round wires, the cables are stripped and inserted into the MTSM. The assembly is then clamped in a fixture, heated with a conductive heating device, and cooled while clamped in place (Figure 12). Tight control of the entire termination process assures consistently high quality solder joints. All conductors are terminated, insulated, sealed, and strain relieved in one simple operation. The completed splice is easy to visually inspect (Figure 13) for joint quality and adhesive flow.

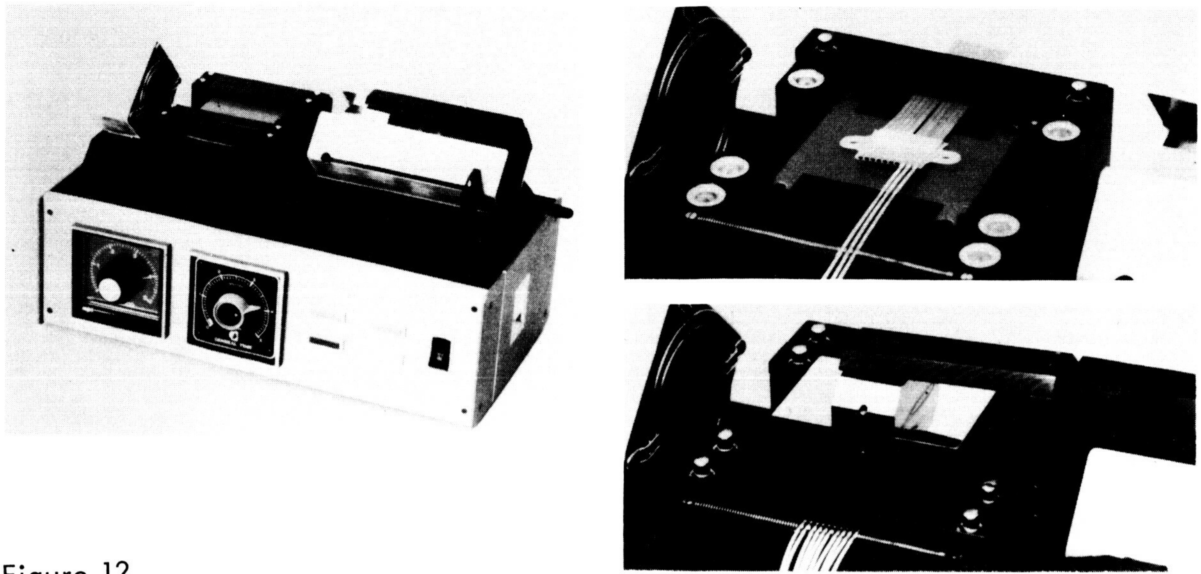
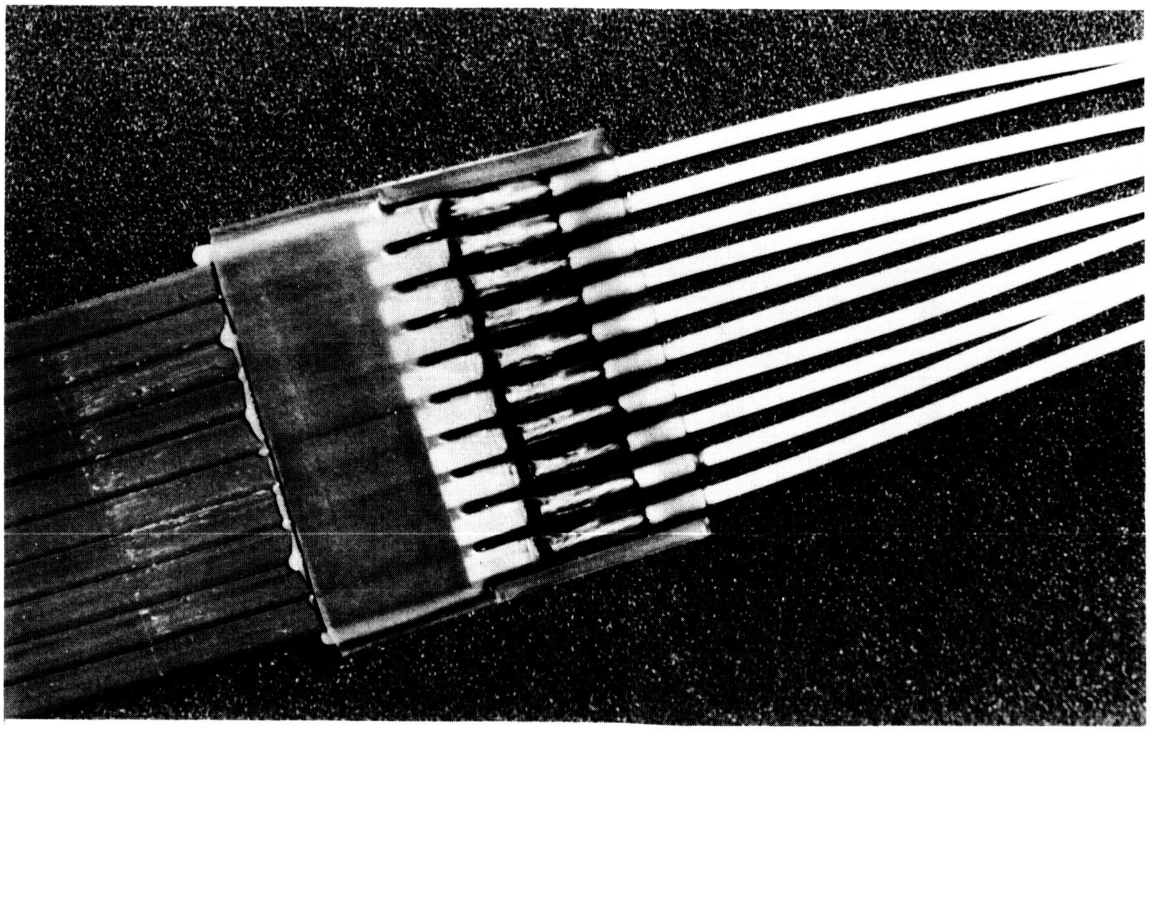


Figure 12.

Figure 13.



Because MTSM's are completely compatible with the modular flat cable, several cable configurations can be terminated to a given size part. For example, a 2-inch wide MTSM on .050" centers (40 circuits) could accommodate: one 2" cable; two 1" cables; a 1" cable and one or two 1/2" cables; and three or four 1/2" cables. Since the bonded-film insulator recovers completely flat and has meltable inserts, individual round wires or an entire flat cable can be left out and the splice will still seal. By having a modular design, eight size cables and eight size MTSM's can be terminated in some 23 different configurations (Figure 14). This versatility—achieved through modular standardization—is what can now make flat cable systems practical, economical, and attractive to the designer.

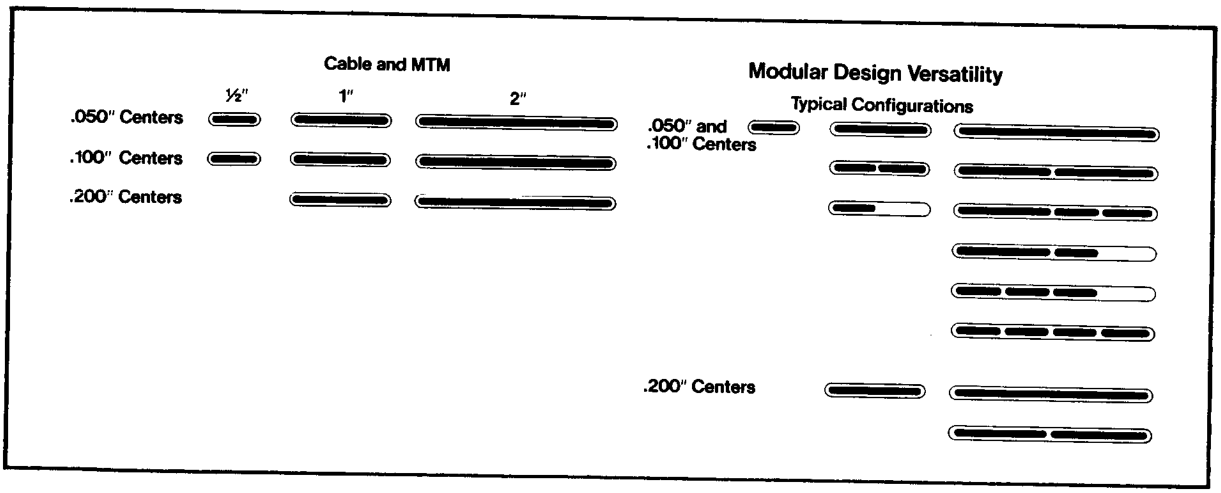


Figure 14

While the MTSM provides strain relief for the round wires and for the flat cable, additional support is needed if the splice is used for adapting to standard circular connectors. Most connectors are available with an adaptor or backshell suitable for heat-recoverable lipped boots, and Raychem has designed a series of strain-relieving flat cable boots to provide the extra support (Figure 15).

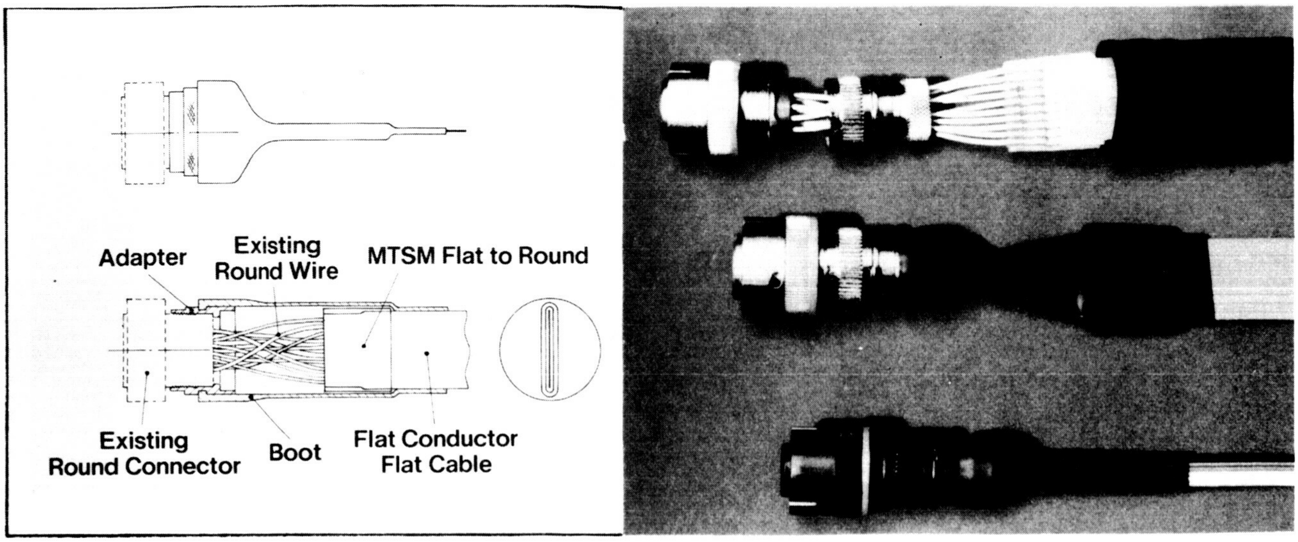


Figure 15.

With the highly reliable flat-to-round transition and the backshell strain relieving boot, flat cable can be used with existing standard connectors without compromising their performance.

A FLAT-TO-FLAT SPLICE

The word "splice" often carries bad connotations and is frequently avoided, but most electronic wiring systems still rely on splicing to achieve wider versatility. A reliable splice, if done properly with the correct device, can simplify wiring systems and reduce congestion in areas of dense interconnection. For these reasons, Raychem has developed a flat-to-flat MTSM similar to the flat-to-round. The design aspects are identical except that the flat-to-flat has a boot section on each end, and a solder-coated metallic connecting strip that is essentially flat (Figure 16).

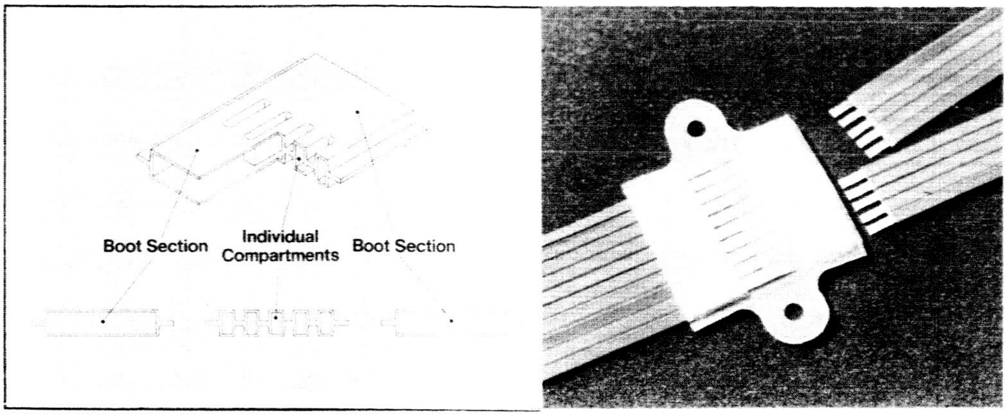


Figure 16

Terminating a flat-to-flat splice is very similar to terminating the flat-to-round. The cables are end-stripped and inserted into the flat-flat MTSM. The assembly is then clamped in a holding fixture, heated under slight pressure, and cooled in place. The entire operation is completed in less than two minutes yielding a multiply terminated, sealed, and strain relieved splice.

The completed splice exhibits the same high quality solder terminations, environmental sealing and inspectability as the flat-to-round splice. Because of the modular cable design and the MTSM compatibility, the flat-flat splice provides a branch harnessing capability. For example, a 2-inch cable can be spliced to four 1/2 inch cables. Provision has also been made for splicing two cables (one on top of the other) to one or two others, where parallel circuits are required (Figure 17).

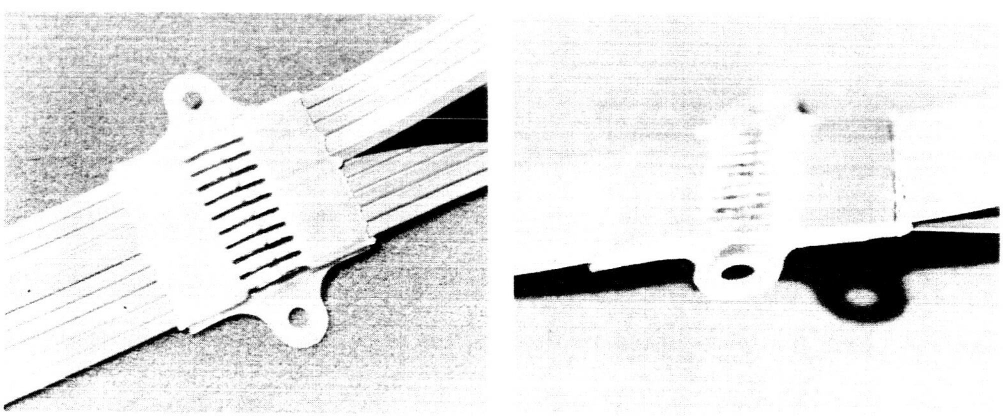


Figure 17

The "thinness" of the terminated MTSM is one of its most attractive features (Figure 18). Being roughly .020" thicker than the cable, the splices may be stacked without taking up excessive space. The thinness and clarity of the insulating material allow parts to be inspected by backlighting, insuring void-free adhesive/sealant. This is especially critical in the area between the stripped conductors (Figure 19). Simarily, the solder joints of both the flat-flat and flat-round splices are fully inspectable for solder flow and wetting.

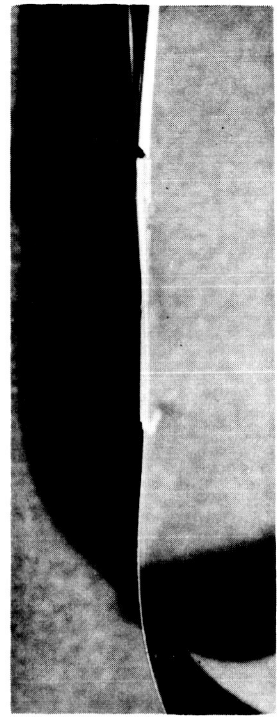


Figure 18

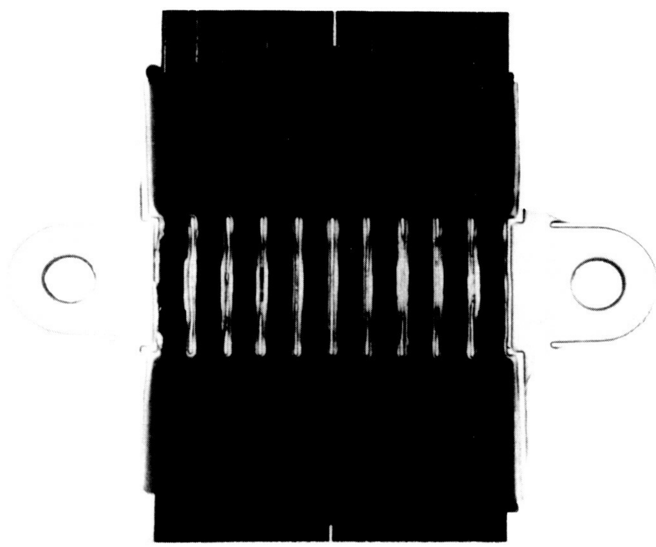


Figure 19.

The innovative design features of the MTSM are dependant upon having materials which can be compatibly combined to meet the stringent requirements for a good splice termination. Taking a systems approach allows complete control over all system components so that all materials may be chosen to be compatible. The all-Polyarylene system under development by Raychem is ideally suited to high reliability flat cable wiring.

In summary, Raychem's Multiple Termination Splice Module and Flat Cable System have seven unique features:

1. Multiple solder termination technique
2. Each individual conductor sealed
3. One-step termination process
4. One-piece assembly
5. Compatible materials and designs
6. Versatility through modular standardization
7. Very low profile

A FLAT CABLE CONNECTOR

Consistent with the goal of having a total solution, the need to connect flat cable directly to system components must be met. A series of flat cable connectors utilizing the multiple solder termination process is currently being developed specifically for the modular flat cable, involving several new concepts in connector design. The connector has provisions for terminating more than one cable in a single connector wafer. The very low profile "wafer" design permits the stacking of connector wafers—with the same or different cable configurations—into variable connector configurations with high density packaging. Each connector wafer has an integral Multiple Termination Module with a boot section on each end, similar to the flat-flat splice. One boot section accepts the flat cable; the other fits over a shoulder on the connector body to seal and strain relieve the terminals, MTM, and connector wafer. Strain relief is thus achieved from the connector body right through the termination area to the cable insulation itself. The connector is a one-piece part, multiply terminated in a single operation, fully sealed, insulated, and inspectable. A primary design requirement being incorporated is low insertion force, with the connector locking itself in place during the engaging cycle.

Figure 20 illustrates the connector/termination concept on a simulated .100" centers connector; the same approach will be used on all center spacings (.050", .100", .200").

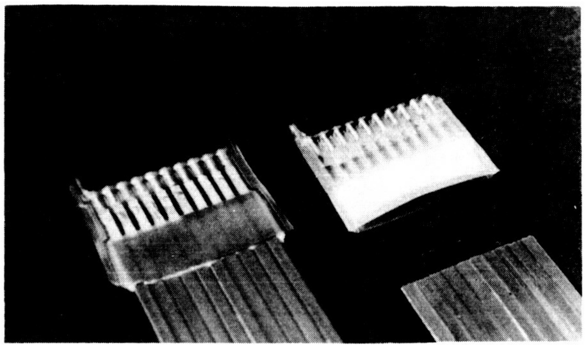
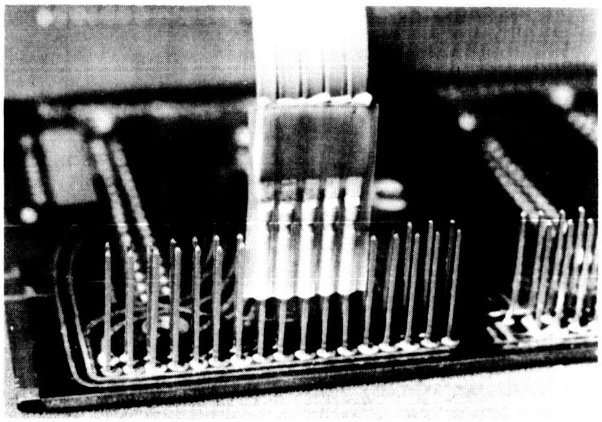


Figure 20

The versatility of the MTM allows it to be made directly into a type of connector. This concept is suitable for interconnections within black boxes or for "internal"wiring in sub-systems. Figures 21 and 22 show two such connector types. In one, a flat cable is terminated to socket contacts inside a flat-to-round MTM which can be plugged directly onto wire wrap pins. The thinness of the termination allows parts to be stacked on .100" square grid with full insulation between layers. Instead of socket contacts, straight or 90° pins can be used for mating to printed circuit board-mounted sockets or for wave soldering in place to a printed circuit board. The MTSM can be mechanically mounted using #4 screws in the holes provided on the sides of the module. The combination of modular flat cables and MTM's lends itself perfectly to interconnection applications—both with and without a connector body—in the flat cable system.



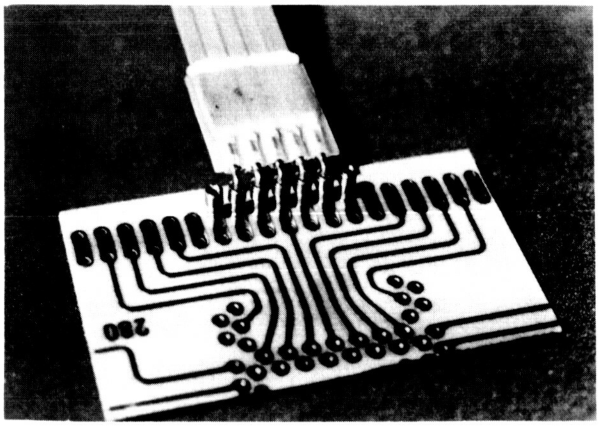


Figure 21

Figure 22

THE DISTRIBUTOR OR JUNCTION BOX

Conventional harnessing is not possible with multiple circuit flat conductor cable. The concept of stringing individual circuits from point-to-point and then bundling together the randomly formed individual wires into a neat, clean harness just doesn't apply. Instead, flat cable must be treated more like multi-conductor patch cords or extension cords, merely carrying a number of organized circuits from one place to the next, in a pre-determined order, simply, cheaply, and reliably. Except in very simple systems, the interconnecting or "wiring" of circuits must be accomplished somewhere else — in the distributor, or junction box. Figure 23 schematically illustrates the distributor concept and indicates why it is an essential part of any major flat cable wiring system.

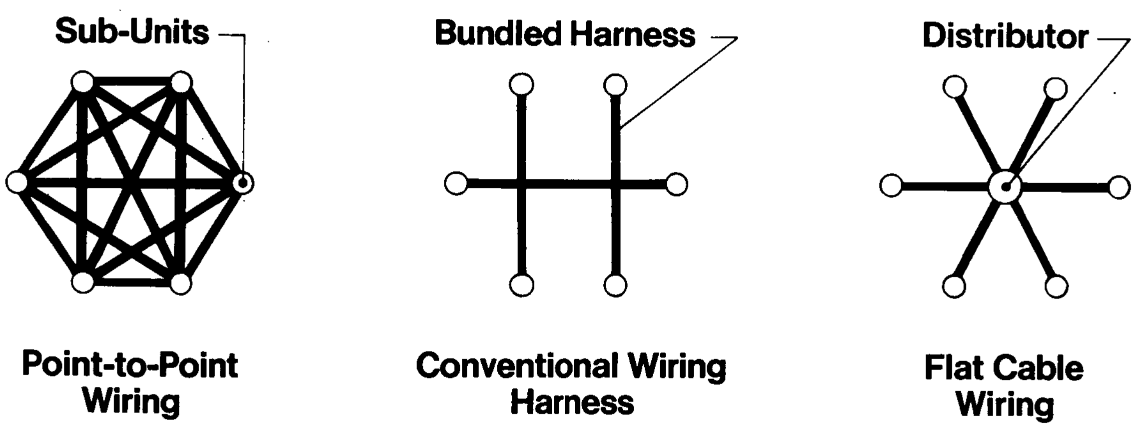


Figure 23. The distributor concept for flat cable wiring.

All interconnection changes, modifications and additions are performed in the distributor. The "tree" type harness and and all its inventory and harness-shop problems are eliminated. 'Harnessing' consists of cutting the flat cable to length and terminating a connector on each end. The modular flat cable design allows many of the cable runs to be the same, thus cutting production costs from the standpoint of volume usage alone.

Since the routing of circuits all takes place within the distributor, main wiring runs can be installed in the early production stages. The final hook-up of circuits (which are constantly being changed) takes place at the very last, when the distributor is 'plugged in'. To meet all of these needs the distributor has very basic, very demanding functional requirements. These are:

Method of bringing circuits in and out
Method of jumpering (interconnecting) circuits
Method for test probing circuits
Method of simplified field maintenance
Method of expansion

The distributor concept currently being developed is seen as a series of modular, multi-plane Matrix blocks, capable of being combined together to meet the size requirements of the system. The Matrix unit (block) would be made up of Input/Output planes, stacked together, and a series of pins to interconnect the planes. While development has progressed only as far as a conceptual model, certain things have been established. With a limited number of pins — ten or less — all possible interconnects can be facilitated by the mere plugging of the correct pin in the right hole. The same circuit can be probed through the pin, changed by changing the pin(without affecting other circuits), and added to by changing or adding pins. The entire operation is capable of being computer controlled and machine 'wired'. It is anticipated that when completed, the design will represent a fully ordered, simplified wiring array.

REPAIR OR MODIFICATION OF THE FLAT CABLE

There will always be times when a conductor needs to be repaired, or times when only a few circuits need to be tapped-off the main cable run (Figure 24). In these instances, it is necessary to gain access to the individual conductor(s) involved. This can be done by several means; but in order to restore complete electrical and mechanical integrity, the cable should again be sealed at the termination.

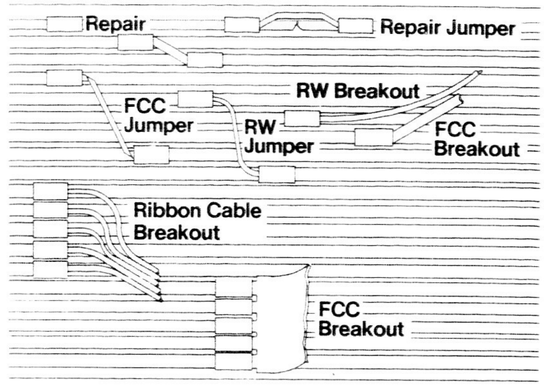


Figure 24

Raychem's Solder Sleeve™ technology combined with the tear-strip design of the extruded flat cable makes repair, jumpering, or tapping-off a simple task. A simple slitting tool (Figure 25) cuts the conductor to be repaired and initiates the tearing of the individually insulated conductor out of the plane of the cable. The two conductor ends are then torn out to the required length and the insulation is removed from each end with a simple hand stripper (Figure 26). A specially designed rectangular Solder Sleeve™ is placed over the stripped ends, along with another round or flat conductor wire if desired.

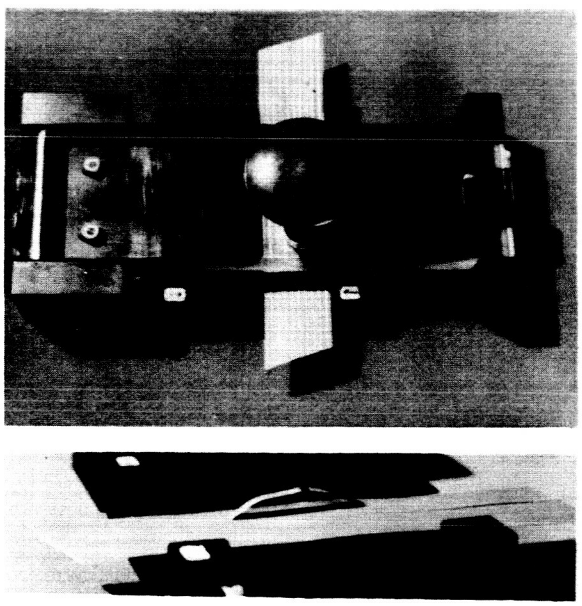


Figure 25

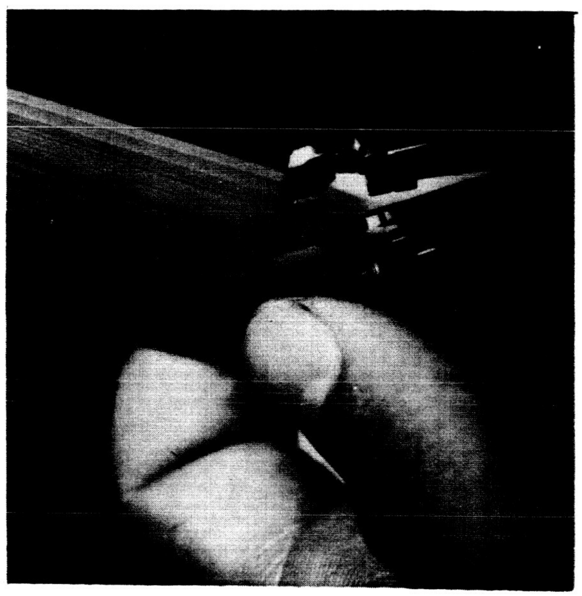


Figure 26

The Solder Sleeve TM (Figure 27) has a solder and flux-coated metallic jumper bar to strengthen the joint between the flat conductors, and a fluxed solder ring around the jumper to supply the extra solder needed for terminating stranded wire. The meltable inserts at each end of the sleeve are Figure-8 shaped (flat cable goes in the lower opening, breakout leads in the upper one) assuring that sealing material will be between the breakout lead and the flat cable after termination. The wires and Solder Sleeve TM assembly is heated with focused infrared energy and within seconds the repair is complete — completely soldered, sealed, isolated, and inspectable (Figures 28 and 29). To prevent further "tearing-out" of the individual conductor, it is recommended that the breakout be clamped within an inch of the termination.

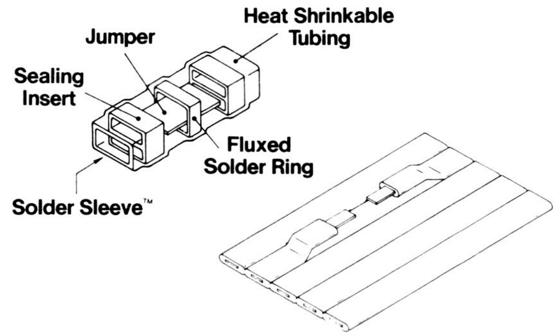


Figure 27

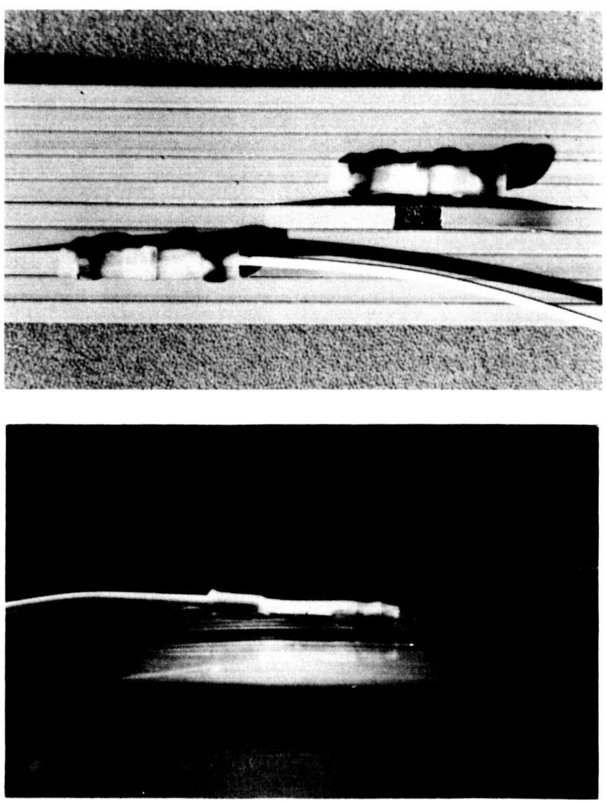


Figure 28

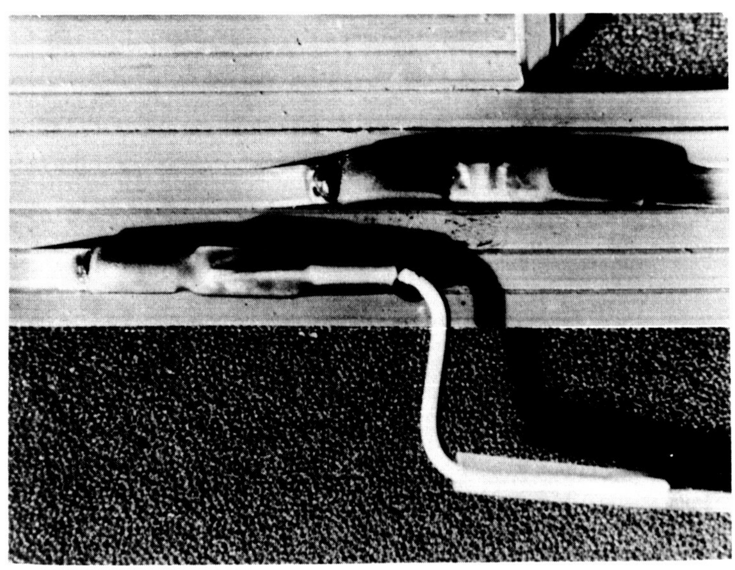


Figure 29

The value of Raychem's tear-groove design cannot be overstated. It allows for easy repair or modification and permits the breaking out of individual or groups of conductors, should that be desired. As such, it can increase the system's flexibility beyond that already achieved through modular standardization. Most importantly, the tear-groove has been designed so that the tear will never propagate to the side, endangering the adjacent conductor's insulation. This feature is not possible with laminated cable.

MATERIALS AND TESTING

Materials

The bonded-film insulating sleeve for the MTSM has been made from Polyvinylidene Fluoride, Ehylene-Chlorotrifluoroethylene Co-Polymer and Polyarylene. (A technical data sheet covering the properties of Polyarylene is in the Appendix). The materials used to seal the individual conductors are hot melt type adhesives specially compounded to be compatible with both the bonded film insulating sleeve and the cable insulation. Material compatibility and sealing characteristics are greatly increased when the entire system — cable and terminating devices — is made from the same basic material. It has been the scope of Raychem's Flat Cable Program to develop such a system. With the introduction of the high temperature melt processable Polyarylene material, it is now possible to have a high-performance, high reliability system with complete design and materials compatibility.

The metallic interconnecting strip in each cavity of the MTSM is a copper alloy coated with a uniform layer of either Sn63 or Sb5 solder, depending upon the operating temperature requirements for the device. The solder surface is, in turn, coated with a controlled amount of rosin flux conforming to MIL-F-14256. The use of Polyarylene and the Sb5 solder material allows the system to have an operating temperature of 200°C.

Testing

The system, as outlined, is being designed to meet or exceed the applicable requirements of MIL-C-55543 and MIL-C-55544, as well as those of Raychem's Specification RT 1450. Although full qualification tests have not been performed on either the cable or the terminating devices, preliminary testing has indicated excellent results in all areas of mechanical and electrical testing.

Tensile tests have shown the cable conductor to neck down and break (10 conductor .100 centers, break strength 200#) outside the terminating device (Figure 30). Voltage break-down tests above 2500 vrms in water (.100 conductor spacing) have been obtained on both flat-to-flat and flat-to-round wire terminations.

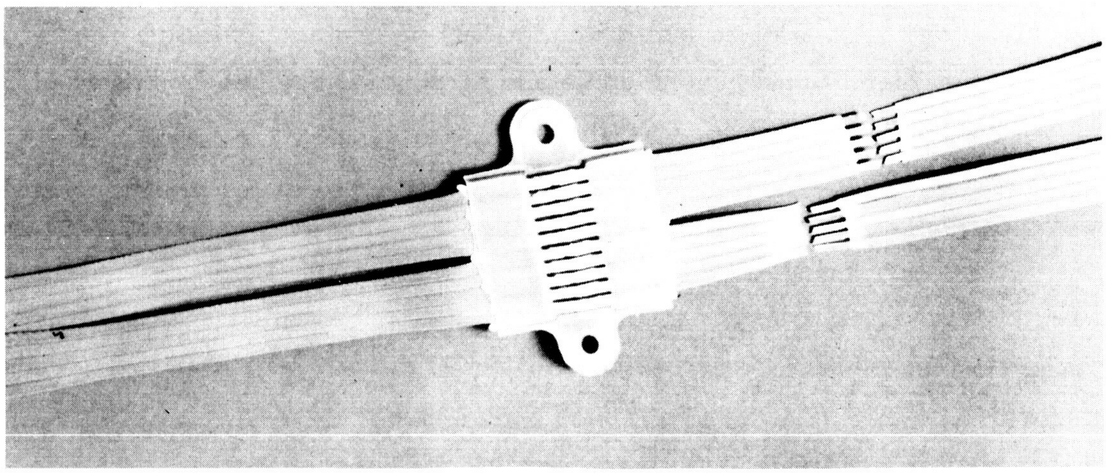


Figure 30

CONCLUSION

While the development program is not complete, there are indications that a total solution is within reach. By choosing standard cable sizes which can be combined modularly and then making all hardware have the same modular versatility, the Flat Conductor Cable System is greatly simplified. Stripping the cable and using a highly reliable solder termination technique—one that is insensitive to centers spacing—improves system performance and realizes the economic advantages of handling smaller conductors with automated multiple terminations. Because all plastic materials are compatible, repairs, splices and connectors can be sealed and strain relieved in a single terminating process. The parts are completely visibly inspectable after termination. The MTSM's —both flat-to-round and flat-flat—are good, simple solutions to their two respective problem areas. The cable represents a major step forward in flat conductor cable design and, again, solves many of the problems associated with flat cable. The repair Solder Sleeves™ are virtually an ideal answer to that need. The connector, while not yet realized in hardware, is committed to the "system" and will fully compliment the versatility and functionality of all the other components. The distributor is purely conceptual at this stage. Nonetheless, it, too, is committed to be system-compatible and the concepts that have been investigated so far show promise of being excellent solutions to the circuit distribution problem area. Raychem's solution is not complete, but it is definitely a fully integrated effort toward a complete design- and materials-compatible system.

MILITARY USAGE OF CONNECTORS

By Richard Schade
DESC

PROPOSED
STUDY PROJECT
PROJECT 5935-1831
FLAT CONNECTORS, FLAT CABLES, AND FIELD
TERMINATION CAPABILITIES AND TECHNIQUES

PURPOSE:

The purpose of this study is to develop and coordinate new general specifications for the military with general purpose parameters and termination data covering flat connectors and flat cables now in the supply system.

RECOMMENDATIONS:

It is recommended of this study that:

1. Flat connectors and flat cables be covered by military specifications.

2. An industry and military meeting be held, prior to any specification action. The purpose of this meeting would be to discuss and come to a final conclusion on each of the following areas:

a. Flat cable

(1) Materials

(a) Conductors - Whether to use copper, which is the most common, or some copper alloy in order to achieve a desired property, or whether to use aluminum in order to save weight. What, if any, other metals may be used based on whether or not they give maximum flexibility with good heat dissipation and have a high current rating.

(b) Coating - Whether to use tin, silver, nickel or any other precious metal which would improve resistance to oxidation at high temperatures, and to enhance subsequent termination processes.

(c) Insulation - Whether to use polyester, polyamide, fluorocarbons (Teflon), or any other compound which has a high tensile strength and high dielectric strength. Resistance to chemical and atmospheric corrosion and to mechanical damage and abrasion should also be taken into consideration.

(d) How the insulation is to be applied - by extrusion, dip coating, or taping and fuzing into a homogeneous wall during processing.

(2) Design

(a) Flat conductors-laminated, extruded, conductors-preinsulated and laminated, coated copper-etched and laminated, coated copper-etched and spray coated, or woven.

(b) Round conductors-laminated, extruded, conductors-preinsulated and laminated, coated copper-etched and laminated, coated copper-etched and spray coated, or woven.

(c) Round multi-conductor cables - bending or weaving.

(d) Whether or not cable should be shielded.

(3) Number of conductors - from two conductors to fifty-seven conductors

(4) Parameters to be specified on a specification sheet

b. Flat connectors

(1) Materials - Whether body should be made of metal or glass filled nylon. What metal with what plating metal should be used on the contacts?

(2) Design - What design would best accomplish the following requirements:

(a) Contacts will be protected if connector is improperly mated.

(b) Insert materials will not chip, crack or break in assembly or in normal service.

(c) Inserts shall positively retain contacts.

(d) If used, shells should retain the insert and protect it from damage.

(3) Number of contacts - from two conductors to fifty-seven conductors.

(4) Parameters to be specified on a specification sheet.

(5) Whether these flat cable connectors shall be covered as non-environmental connectors under existing specification document MIL-C-55544 or as non-environmental connectors under new specification document (See Appendix IA)

DISCUSSION:

Definitions: The following two definitions are given: First, a flat conductor cable can be described as any cable consisting of parallel conductors, or a combination of conductors, held in a position by either being laminated between thin, flexible, plastic insulating films, by being woven, or by any other method whereby the conductors are held flat and parallel. Secondly, a flat cable connector is defined as a mated separate plug and receptacle, designed to connect a cable with another cable, printed circuit board, box, or component, thereby giving flat cable good field termination capabilities.

APPLICATIONS:

The military has used flat cables and flat cable connectors in the Missile Control Center of the Poseidon Fire Control System, on the surveyor moon trips, as a part of satellite, missile and rocket systems, and airbourne electronics and ground support systems.

In the commercial field, the flat cables and flat cable connectors are employed in data processing equipment, control instruments, and oscillating devices for aircraft antenna arrays. With the increased uses of digital computers, a requirement has been created for signal bus cables which are used to carry many digital (pulse) signals from one section of the computer to another. Flat cables are used for this purpose.

FINDINGS:

Data was requested from the Military Services and Industry for the flat cables and flat cable connectors found in the Federal Stock Classes 6145 and 5935. The flat cables in Appendix II are those for which data was made available.

Original Equipment Manufacturers (OEM) are beginning to use flat cable and flat cable connectors on their drawing or specification and on their non-standard part submittal.

It was found that the electrical, mechanical and environmental requirements varied among flat cable and flat cable connectors of the same style.

CONCLUSION:

1. Standard terminology, requirements and test procedures.

2. Preferred flat cables and flat cable connectors will be available for standard parts selection by users.

3. Quality assurance provisions to assure a quality product.

RESPONSES AND ANALYSIS:

Reference letter dated 3 January 1972, title Flat Cable and Flat Cable Connectors (See attachment 1)

MILITARY RESPONSES: (To reference letter above)

Air Force - No data submitted except to comment that MIL-C-55543 and MIL-C-55544 will be used as standards in updating MIL-C-83723/80 and /81 for use with flat cable.

Navy - The following data was submitted for consideration

(1) NAVORD W56117B, "Performance Specification for Connector, Electrical, Rack and Panel Type with Contacts on 0.100 Grid"

(2) Navy Special Projects Office Dwg. No. 2826728, entitled "Connector Assembly"

(3) Navy Special Projects Office Dwg. No. PL2826728, entitled "Connector Assembly"

(4) BUWEPS Specification Control Dwg. No. 2465230, entitled "Cable, Electrical, Special Purpose, Ribbon and Component Parts"

(5) NAVORD Dwg. No. 755548, entitled "Cable Assembly"

Army - Data submitted consisted of MIS-11259, titled "Missile Interim Specification for Cable, Special Purpose, Electrical, Multiple Conductor, Flat"

INDUSTRY RESPONSE: (To reference letter above)

Total number of responses received to the inquiry letter - - - 21
Number of companies submitting data - - - - - - - - - - - - - - 12
Number of letters received without data - - - - - - - - - - - - 9

SPECIFICATIONS RECEIVED:

Boeing
Commanding Officer, Naval Air Engineering Center
Electronics Command (U.S. Army)
Institute of Printed Circuits

DEFENSE SUPPLY AGENCY
DEFENSE ELECTRONICS SUPPLY CENTER
DAYTON, OH 45401

IN REPLY REFER TO: DESC-EMT

3 January 1972

SUBJECT: Request for Technical Data on Flat Connectors, Flat Cables, and Field Termination Capabilities and Techniques; Project Number 5935-1831

TO: Military Distribution

1. An Engineering Practices Study Project 5935-1831 was initiated to review the number of flat connectors/flat cables presently utilized in the supply system, but not covered by military specification. The ultimate results of this study will be the issuance of a new general specification with general purpose parameters and termination data.

2. Request your input and comments concerning each section of the general specification. Comments are required at this Center on 3 March 1972. Military review activities should forward comments through their normal chain of command to their respective departmental custodian by 15 February 1972, to allow time to prepare a coordinated departmental reply. Departmental custodians should send a copy of their comments to the Commanding General, U. S. Army Electronics Command, ATTN: AMSEL-PP-EM, Fort Monmouth, NJ 07703.

3. Additional information may be obtained by calling Mr. Robert Julius or Mr. R. Schade, area code 513, telephone 252-6551, extension 5391, or AUTOVON 989-5391.

FOR THE COMMANDER:

J. A. Kobylack

J. A. KOBYLACK
Chief, Transmission Devices
Branch

DEFENSE SUPPLY AGENCY
DEFENSE ELECTRONICS SUPPLY CENTER
DAYTON, OH 45401

IN REPLY REFER TO: DESC-EMT

3 January 1972

SUBJECT: Request for Technical Data on Flat Connectors, Flat Cables, and Field Termination Capabilities and Techniques; Project Number 5935-1831

Industry Distribution

Gentlemen:

In an effort to promote engineering standardization, the Department of Defense has initiated an Engineering Practice Study, Project Number 5935-1831, to develop and coordinate new general specifications with general purpose parameters and termination data covering flat connectors and flat cable.

Manufacturers and Users of flat connectors/flat cable are invited to participate in the preparation of the initial draft by submitting their recommendations for the following sections:

a. Scope

b. Applicable Documents

c. Requirements

d. Quality Assurance Provisions

e. Terms and Definition

Specific items may be outlined as follows:

a. Federal Stock Number (FSN), where available

b. Manufacturers Part Number or Military Drawing Number

c. The Black-Box Application, e.g., AN/APQXXX Radar

d. Weapon System(s) or Weapon System Supporting Equipment(s)

It is requested that technical data and recommendations be forwarded to the Defense Electronics Supply Center before 3 March 1972.

DESC-EMT
SUBJECT: Request for Technical Data on Flat Connectors, Flat Cables, and Field Termination Capabilities and Techniques; Project Number 5935-1831

The data must be furnished at no cost to the Government.

Additional information may be obtained from Mr. R. Julius or Mr. R. Schade by calling area code 513, telephone 252-6551, extension 5391.

Sincerely,

J. A. Kobylack

J. A. KOBYLACK
Chief, Transmission Devices Branch

APPENDIX I

DRAFT FOR FLAT CABLE

CABLE, ELECTRICAL, FLAT MULTICONDUCTOR, FLEXIBLE, UNSHIELDED

1. SCOPE

1.1 This specification covers flat multiconductor, unshielded, flexible cables suitable for general use in aerospace, ground and shipboard applications to provide minimum size, weight, and space saving consistent with service requirements. The cables are constructed with parallel copper conductors either laminated in position, or etched in position, between layers of insulation.

2. REQUIREMENTS

2.1 Detail requirements for individual cable styles. The requirements for the individual cables under this specification shall be as specified herein and in accordance with the applicable military specification sheets. In the event of discrepancy between this specification and the requirements of the applicable military specification sheet, the requirements of the military specification sheet shall govern.

3.1 Materials..

3.1.1 Conductors. Unless otherwise specified, conductor material shall be copper of 100 percent conductivity for strip-conductor constructions, or 97 percent conductivity for etched-conductor constructions in accordance with International Annealed Copper Standards (IACS). Conductor material shall otherwise conform to the following:

Strip-conductor constructions

Slit-conductors	-Unless otherwise specified, solid soft, or annealed ETP flat copper, without burrs, per QQ-C-576.
Flattened-round-wire conductors	Type S, solid, soft or drawn annealed, bare round copper wire per QQ-W-343, flattened to size.
Flat conductors	- Soft temper, oxygen free copper wire per QQ-C-502.

Etched-conductor constructions

Etched-conductors	- Soft, or annealed, rolled copper foils per MIL-F-55561 or electrolytic deposited copper with a minimum purity of 99.5 percent.

When specified, certification of conductor material shall be furnished by the manufacturer with each shipment of cable.

3.1.1.1 Thickness. Etched conductor shall be fabricated from rolled copper foil conforming to QQ-C-576. Thicknesses shall be in conformance to table I. The foil may be chemically treated to produce an oxide coating. Imperfections in the foil prior to treatment shall be limited to scratches and pits with a maximum depth of 10 percent of thickness and pinholes of 0.003 inch maximum diameter with a maximum of three per square foot.

TABLE 1
THICKNESS OF COPPER FOIL

Copper Foil Weight (oz/sq ft)	Nominal Thickness (inches)	Tolerance (inches)
4	0.0054	±0.0008

3.1.1.2 Insulation. The cable insulation shall consist of a polyamide layer and a bonding material layer. The bonding material shall be a polyamide adhesive Additional bonding material may be added to fill voids between conductors. Alternate constructions meeting the requirements of this specification are acceptable. The insulation and bonding layers shall be the thickness specified in table II.

TABLE II
THICKNESS OF INSULATION LAYERS

Layer	Laminate Thickness
Polyamide insulation	0.003 ± 0.0005 inch
Bonding layer	0.001 ± 0.0005 inch

3.1.2 Conductor width. The conductor width shall meet requirements excluding imperfections such as pinholes, scratches, and nicks which shall not exceed one per linear inch and reduce minimum conductor width by more than 20 percent. Protrusions on conductors shall not exceed one per linear inch and reduce the minimun spacing by more than 20 percent. All residual copper not shown on artwork between conductors shall be removed. The etching process shall not deleteriously affect the insulation.

3.1.3 Conductor coating. Coated conductors shall be as specified in the applicable specification sheet.

3.1.4 Termination pads. Termination pad exposure shall be accomplished so that the delamination of the copper on the inside diameter of a punched or drilled hole shall not exceed 30 percent of the circumference. Shift of the prepunched coverlay shall leave a minimum of 0.005 inch exposed conductor around the terminal hole. In no case shall the edge of the insulation expose an adjacent conductor. Prepunched coverlays shall not expose the pad edge (fail to capture) for more than 90 degrees.

3.2 Performance and product characteristics

3.2.1 Dimensions. Assemblies of etched flat cable shall be dimensionally examined to assure compliance with the requirements of applicable drawings.

3.2.2 Bond strength. The bond strength between the insulation and the copper shall be not less than 3 pounds per inch of width.

3.2.3 Delamination. The insulation layers shall be bonded to the conductors and to each other over the full area of cable. The cable shall be free of blisters, cracks, fogginess, etc.

3.2.4 Copper brittleness. The copper conductor shall show no fractures when it is bent back on itself 180 degrees and pressed flat.

3.2.5 Electrical requirements.

3.2.5.1 Continuity. Circuits in each cable shall be continuous. No circuit shall have a resistance greater than one ohm.

3.2.5.2 Insulation resistance. Where conductors are laminated between insulation sheets, the insulation resistance shall be 500 megohms minimum for the cable by itself. When the assembly has connectors, the connector specification shall govern if the connector resistance requirements is lower.

3.2.5.3 Dielectric strength. The completed assembly shall meet the minimum test voltage of 1000 volts direct current (Vdc). Each conductor shall be tested to all other adjacent conductors. The insulation shall not break down.

3.2.5.4 Conductor resistance. Conductors, which fail to meet the minimum line width as specified in 3.1.2 are acceptable if the resistance requirement or table III is met.

3.3 Environmental and service conditions.

3.3.1 Temperature.

3.3.1.1 Operating

3.3.1.1.1 High temperature. The cable shall not be damaged nor shall the performance be impaired during operation at ambient temperatures to plus 60 degrees Centigrade (C) (plus 140 degrees Fahrenheit (F)).

3.3.1.1.2 Low temperature. The cable shall not be damaged nor shall the performance be impaired during operation at ambient temperatures to minus 31.7 degrees C (minus 25 degrees F).

3.3.1.2 Nonoperating

3.3.1.2.1 Storage and transit. The cable shall not be damaged nor shall the performance be impaired by storage or transportation at temperatures ranging from minus 62.2 to plus 68.3 degrees C (minus 80 to plus 155 degrees F).

3.3.1.2.2 Temperature shock. The cable shall not be damaged nor shall the performance be impaired by exposure to plus 285 plus or minus 10 degrees C (plus 545 plus or minus 18 degrees F) heat for one minute of plus 371 plus or minus 10 degrees C (plus 700 plus or minus 18 degrees F) for 20 seconds.

3.3.1.2.3 Temperature cycle. The cable shall not be damaged nor the performance impaired by exposure to temperature cycling between plus 68.3 plus or minus 3 degrees C (plus 155 plus or minus 5 degrees F) and minus 62.2 plus or minus 3 degrees C (minus 80 plus or minus 5 degrees F).

3.3.2 Shock

3.3.2.1 Operating. The cable shall not be damaged and shall continue to perform during and after any shock encounted while in operation.

3.3.2.2 Nonoperating.The cable shall not be damaged nor shall the performance be impaired after exposure to handling and transit shocks.

3.3.3 Vibration

3.3.3.1 Operating. The cable shall not be damaged nor shall the performance be impaired during exposure to operational vibration.

3.3.3.2 Nonoperating. The cable shall not be damaged nor shall the performance be impaired after being exposed to transit vibration.

3.3.4 Shock-vibration

3.3.4.1 Operating. Not applicable.

3.3.4.2 Nonoperating. The cable shall not be damaged nor shall the performance be impaired after being exposed to transit-shock-vibration.

3.3.5 Humidity.

3.3.5.1 Operating. Not applicable.

3.3.5.2 Nonoperating. The cable shall not be damaged nor shall its performance be impaired after exposure to relative humidity of 95 plus or minus 5 percent at plus 71 plus or minus 2.8 degrees C (plus 160 plus or minus 5 degrees F).

3.4 Workmanship.

3.4.1 Appearance. The finished assembly shall be free of loose parts and

crazes or cracks in the insulating material, show no signs of separation or delamination, and shall have all contact areas properly exposed and finished. Edges shall be cut smoothly. No individual voids shall bridge adjacent conductors. Line voids along the edges of conductor are acceptable if not longer than one inch.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection. Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facility or any commercial laboratory acceptable to the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.2 First article inspection. When specified in the contractual document, a sample consisting of 25 feet of flat cable, manufactured under the same conditions as those proposed for subsequent production, shall be subjected to First article inspection. Accomplishment of first article inspection shall be as specified in the contract. If the first article sample does not meet the requirements of this specification and applicable drawings, it shall be rejected. Subsequent units will not be considered for acceptance until Government approval of the first article sample has been obtained. Units subjected to first article inspection shall have successfully passed acceptance inspection. Testing of the first article sample, shall be conducted in accordance with the corresponding test paragraphs.

4.3 Quality conformance inspection

4.3.1 Sampling for acceptance inspection. Sampling for visual examination and for testing shall be conducted on a random sample selected from each production lot or less in accordance with MIL-STD-105 at the specified acceptable quality level (AQL).

4.3.2 Lot formation. The lot size shall not exceed the quantity of items produced in one continuous operation by the same manufacturer and manufactured in accordance with the same drawing, drawing revision, specification, and specification revision.

4.3.3 Classification of defects. The classification of defects and AQL shall be as specified in table V. Characteristics not otherwise defined are classified as minor with an AQL of 4.0 percent.

4.3.4 Acceptance inspection. Acceptance inspection of samples specified in 4.3.1, to determine compliance with the characteristics listed in table VI, shall be conducted in accordance with the corresponding test paragraphs.

TABLE III
FIRST ARTICLE INSPECTION

Characteristic	Requirement Source	Test Paragraph
Conductor width	Applicable Drawing	4.5.3.1.4
Termination	3.1.4	4.5.3.2.2
Dimensions	3.2.1	
Bond strength	3.2.2	4.5.3.2.3
Delamination	3.2.3	4.5.3.2.4
Copper brittleness	3.2.4	4.5.3.2.1
Continuity	3.2.5.1	4.5.3.1.1
Insulation resistance	3.2.5.2	4.5.3.1.2
Dielectric strength	3.2.5.3	4.5.3.1.3
Conductor resistance	3.2.5.4	4.5.3.1.4
Temperature	3.3.1	4.5.4.1
Shock	3.3.2	4.5.4.3
Vibration	3.3.3	4.5.4.4
Shock-vibration	3.3.4	4.5.4.5
Humidity, nonoperating	3.3.5.2	4.5.4.6.2
Workmanship	3.4	4.3.5

TABLE IV
CLASSIFICATION OF DEFECTS

Categories and Defects	Method of Inspection	Sources
CRITICAL		
None		
MAJOR		
Group A (AQL 0.0)		
101 Continuity	Meter	3.2.5.1
102 Dielectric strength	Dielectric strength tester	3.2.5.3
Group B (AQL 0.10)		
104 Excessive pinholes in copper	Visual	3.1.1.1
105 Conductor width	Visual	3.1.2
Group C (AQL 0.25)		
106 Delamination	Visual and wicking test	3.2.3
107 Dimensional requirements	Gage	3.2.1
108 Bond strength	Universal testing machine	3.2.2
109 Copper brittleness	Visual	3.2.4
110 Crazes, cracks	Visual	3.4.1
111 Plating	Visual	3.1.3
112 Insulation resistance	Megohmeter	3.2.5.2
113 Broken connector	Visual	3.4.1
114 Nicks in edge of insulation	Visual	3.4.1
MINOR		
Group A (AQL 1.0)		
201 Voids in potting	Visual	3.4.1
Group B (AQL 4.0)		
205 Termination pad exposure	Visual	3.1.4

TABLE V
ACCEPTANCE INSPECTION

Characteristic	Requirement Source	Test Paragraph
Conductor width	Applicable Drawing and 3.1.2	4.5.3.1.4
Terminal pad exposure	3.1.4	4.5.3.2.2
Bond strength	3.2.2	4.5.3.2.3
Delamination	3.2.3	4.5.3.2.4
Copper brittleness	3.2.4	4.5.3.2.1
Continuity	3.2.5.1	4.5.3.1.1
Insulation resistance	3.2.5.2	4.5.3.1.2
Dielectric strength	3.2.5.3	4.5.3.1.3
Workmanship	3.4	4.3.5

4.3.5 Visual inspection. The finished cable shall be inspected to assure compliance with 3.4.1. Inspection for pinholes in the conductor for compliance with 3.1.1.1 shall be carried out visually over a lighted table. Magnification not exceeding 10X may be used during visual inspection.

4.4 Inspection equipment. The inspection equipment for conducting examinations and tests shall be identified in the individual test paragraphs.

4.5 Test methods and procedures.

4.5.1 Test conditions. Unless otherwise specified herein, the following conditions shall be used as a basis to establish performance requirements:

a. Temperature — Room ambient

b. Altitude — Facility ambient

c. Humidity — Relative humiduty 40 to 65 percent.

4.5.2 Test sequence. Testing sequence shall be at the option of the contractor.

4.5.3 Performance tests.

4.5.3.1 Electrical

4.5.3.1.1 Continuity. Conductors shall be tested for continuity between each exposed termination by use of a meter type continuity tester. No circuit shall have a resistance greater than 1.0 ohm.

4.5.3.1.2 Insulation resistance. Insulation resistance measurement shall be made by placing the cable between two conductive metal sheets which are mutually grounded. Measurements shall be made between all conductors and ground using a standard megohmmeter. A minimum spacing of 0.040 inch shall be maintained between exposed pads and the ground sheets. Insulation resistance shall be measured at 500 Vdc.

4.5.3.1.3 Dielectric strength. Testing shall be done without water immersion. Each conductor shall be high voltage tested to all adjacent conductors at 1,000 Vdc. Each portion of the cable insulation shall be high-voltage tested to ground by holding a ground electrode against it and applying voltage to conductors. Voltage shall remain applied until transient charging current stabilizes.

4.5.3.1.4 Conductor resistance. The conductor shall be tested for maximum resistance using a suitable bridge that has an accuracy of 2.0 percent. The measurements shall be corrected to plus 20 degrees C (plus 68 degrees F).

4.5.3.2 Mechanical

4.5.3.2.1 Copper brittleness test. A specimen as specified in figure 1a that has been through the cable manufacturing process shall be tested for brittleness. The specimen shall have the coverlay removed from one side. If a surface treatment is used in the copper, it shall be removed chemically from the exposed side. The method used to remove the coverlay shall in no way result in degradation of the test specimen. The specimen shall be bent double and pressed flat on itself with the copper exposed. A visual examination (10X) of the copper at the bend line shall meet the requirements of 3.2.4.

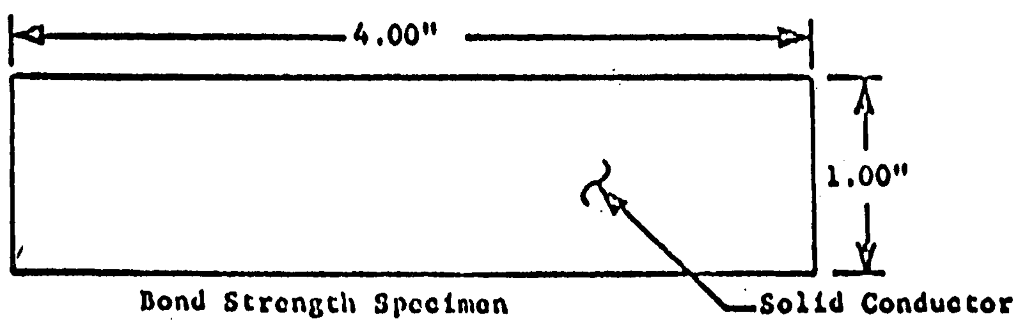
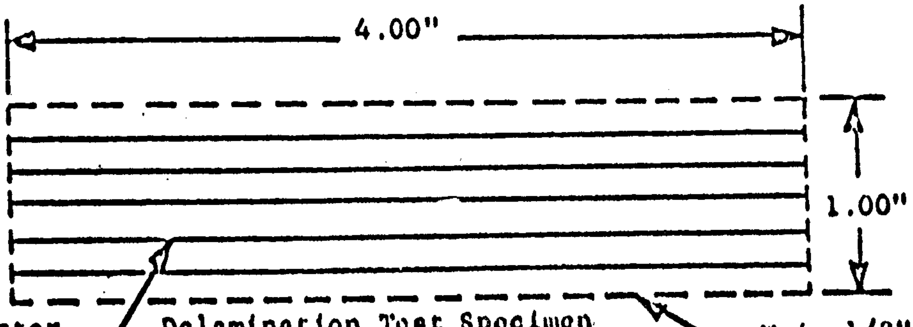


Fig. 1a

4.5.3.2.2 Termination pad. The termination pad exposure shall be visually examined to assure compliance with 3.1.4. Magnification not exceeding 10X may be used during visual inspection.

4.5.3.2.3 Bond strength. Test specimens shall be incorporated in the artwork and processed with the cables for each increment of material manufactured through the coverlay operation. The bond strength specimen (figure 1a) shall have the coverlay removed as defined in 4.5.3.2.1 and shall be trimmed from the cable with a slight excess of base insulation at each end, and the sides trimmed so that there is no capture by the insulation or adhesive. The test specimen shall be prepared for peel test by peeling the insulation layer from the copper a distance adequate to allow the knurled jaws to grip the copper. A steady pull, between 90 and 180 degrees, shall be applied to the insulation bond line with jaws traveling at the approximate rate of 2 inches per minute. The bond strength shall be determined when a constant reading is obtained during the pull. Minimum bond strength shall conform to 3.2.2. The failure of the polyamide insulation during peel test shall not be cause for rejection.

4.5.3.2.4 Delamination. Test specimens shall be incorporated in the artwork and processed with the cables for each increment of material manufactured through the coverlay operation. The delamination test specimen (figure 1b) shall be trimmed to expose the copper conductors.



Delamination Test Specimen
Fig. 1b.

The test specimens shall be inspected visually for delamination of the bonded insulation layers as specified in 3.2.3. Delamination is indicated by blisters, cracks, fogginess, etc., when observed looking at the flat area of the specimen. Specimen shall also pass one of the following wicking tests:

Test a. The cable shall be immersed in a saturated solution of sodium sulfide at plus 23 plus or minus 2 degrees C (plus 73.4 plus or minus 3.6 degrees F) for 30 plus or minus one minute and rinsed in clean running water.

Test b. The cable shall be immersed in a saturated solution of 25 percent by volume hydrochloric acid at plus 23 plus or minus 2 degrees C (plus 43.4 plus or minus 3.6 degrees F) for 30 plus or minus one minute and rinsed in clean running water.

The encompassing seal shall be sufficient to prevent any conductor from

discoloring more than 0.25 inch from the sheared end. Test a shall be used except in the event conductor color precludes definitive results.

4.5.4 Environmental tests

4.5.4.1 Temperature

4.5.4.1.1 Operating. The cable shall be tested in accordance with MIL-STD-810, Method 501, Procedure I for high temperature operation except that the internal chamber temperature shall be stabilized at plus 60 plus or minus 2.8 degrees C (plus 140 plus or minus 5 degrees F) for a period of 6 hours plus or minus 10 minutes. MIL-STD-810, Method 502, Procedure I shall apply for low temperature test except that the internal chamber temperature shall be stabilized at minus 31.7 plus or minus 2.8 degrees C (minus 25 plus or minus 5 degrees F)for a period of 6 hours plus or minus 10 minutes. During each test the cable shall pass the continuity test of 4.5.3.1.1.

4.5.4.1.2 Nonoperating

4.5.4.1.2.1 Storage and transit. The cable shall be tested in accordance with MIL-STD-810, Methods 501 and 502, Procedure I except that the temperatures shall be plus 68.3 plus or minus 2.8 and minus 62.2 plus or minus 2.8 degrees C (plus 155 plus or minus 5 and minus 80 plus or minus 5 degrees F). Upon completion of the tests and after return to room temperature, the cable shall meet the continuity and dielectric strength requirements of 4.5.3.1.1 and 4.5.3.1.3.

4.5.4.1.2.2 Temperature shock. Three test specimens as specified in figure 1a and one specimen as specified in figure 1b shall be placed on a flat rigid asbestos surface. An aluminum plate 1/2 inch thick of dimensions which will cover the test specimens, heated to plus 285 plus or minus 10 degrees C (plus 545 plus or minus 18 degrees F), shall be placed on the specimens for one minute. It is not required that the aluminum plate be maintained at plus 285 degrees C (plus 545 degrees F) for one minute. The bond strength specimen shall be placed so that the exposed copper contacts the aluminum plate. After exposure, the three test specimens as specified in figure 1a shall pass the peel test in 4.5.3.2.3. One test specimen as specified in figure 1b shall pass examination and test for delamination as specified in 4.5.3.2.4.

4.5.4.1.2.3 Temperature cycle. Three test specimens as specified in figure 1a and one as specified in figure 1b shall be placed in an oven at plus 71 plus or minus 2 degrees C (plus 160 plus or minus 5 degrees F) for 30 plus or minus 3 minutes. Each specimen shall then be removed from the oven and placed in a cold chamber at minus 62.2 plus or minus 3 degrees C (minus 80 plus or minus 5 degrees F) for 30 plus or minus 3 minutes. The test specimens shall then be returned to the oven and the cycle repeated for a total of three times. The elapsed time for transfers between the oven and cold chamber shall not exceed 2 minutes. After exposure, the three test specimens as specified in Figure 1a shall pass the peel test in 4.5.3.2.3. One test specimen as specified in Figure 1b shall pass the examination and test for delamination as specified in 4.5.3.2.4.

4.5.4.3 Shock

4.5.4.3.1 Operating. The sample shall be subjected to no more than 3g0g. During shock, the cable shall pass the continuity test of 4.5.3.1.1.

4.5.4.3.2 Nonoperating. The test specimen shall be mounted on a shock fixture and submitted to 100 gravity units (g), 10 milliseconds (ms) half sine wave shocks along the three axes. Upon completion of the test, the sample will be inspected for physical damage and shall pass the continuity test of 4.5.3.1.1.

4.5.4.4 Vibration

4.5.4.4.1 Operating. The cable, installed as specified in 4.5.4.3.2, shall be subjected to vibration stimuli sufficient to produce but not exceed the vibration levels of figure 2. During vibration, the cable shall pass the continuity test of 4.5.3.1.1.

4.5.4.4.2 Nonoperating. The cable, installed as specified in 4.5.4.3.2, shall be subjected to transportation vibration in accordance with MIL-STD-810, Method 514 as modified by figure 2 herein, applied at the scuff pad locations. Vibration shall last for 50 hours in each of three orthogonal axes. Upon completion of the test, the cable shall be inspected for physical damage and shall pass the continuity test of 4.5.3.1.1.

4.5.4.5 Shock-vibration

4.5.4.5.1 Operating. Not applicable.

4.5.4.5.2 Nonoperating. The cable, installed as specified in 4.5.4.3.2, shall be subjected to the random vibration of figures 3a, 3b, and 3c for 39.7 hours in each of three orthogonal axes and of figures 4a, 4b, and 4c for 3.4 hours in each of three orthogonal axes. Upon completion of each of the two vibration tests, the cable shall be inspected for physical damage and shall pass the continuity test of 4.5.3.1.1.

4.5.4.6 Humidity

4.5.4.6.1 Operating. Not applicable.

4.5.4.6.2 Nonoperating. The cable shall be tested in accordance with MIL-STD-810, Method 507. Upon completion of the test, the cable shall pass the insulation and dielectric tests of 4.5.3.1.2 and 4.5.3.1.3.

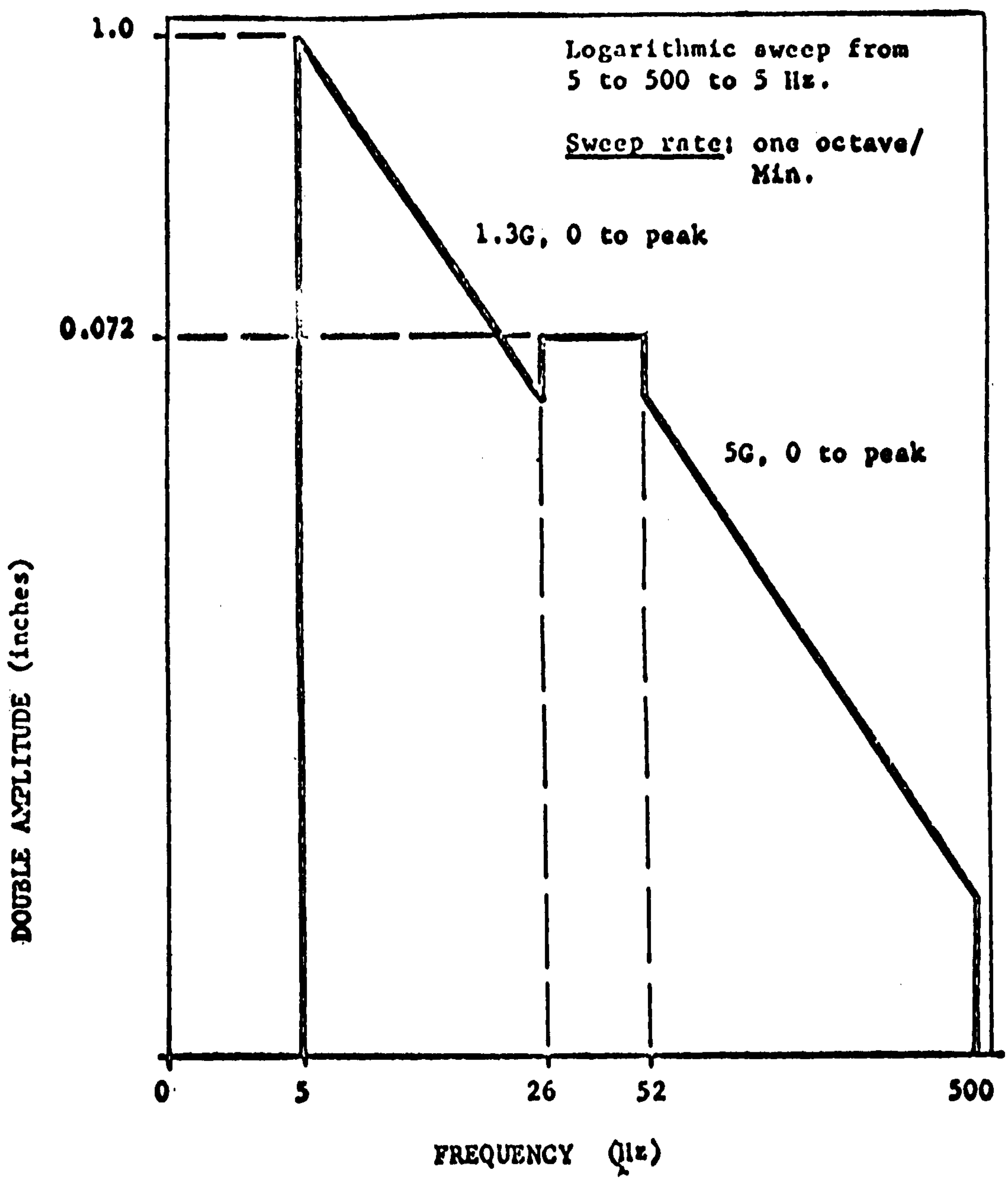


Figure 2. System Vibration

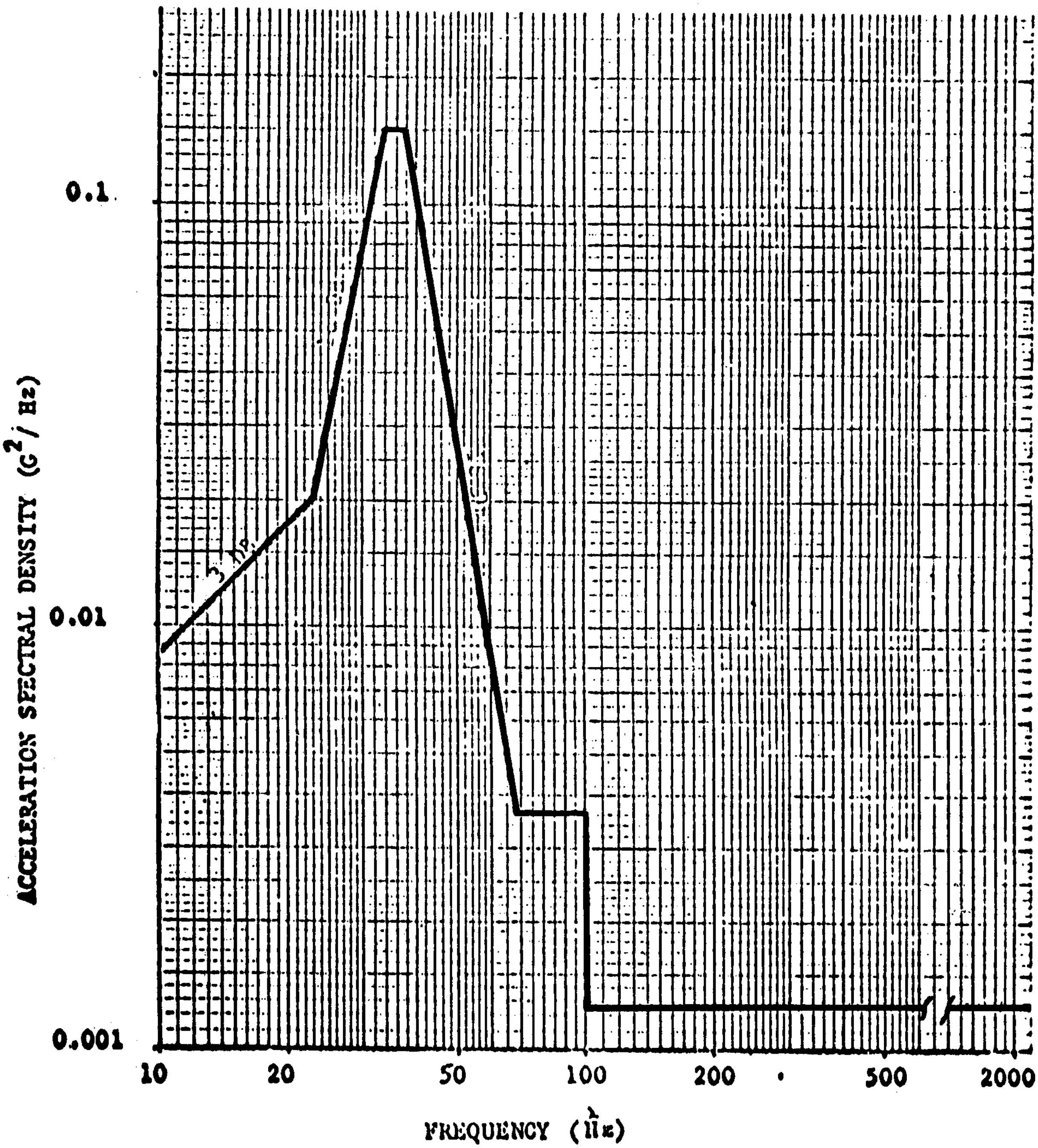


Figure 3a. Vibration Levels, Vertical, Stowed in Vehicle

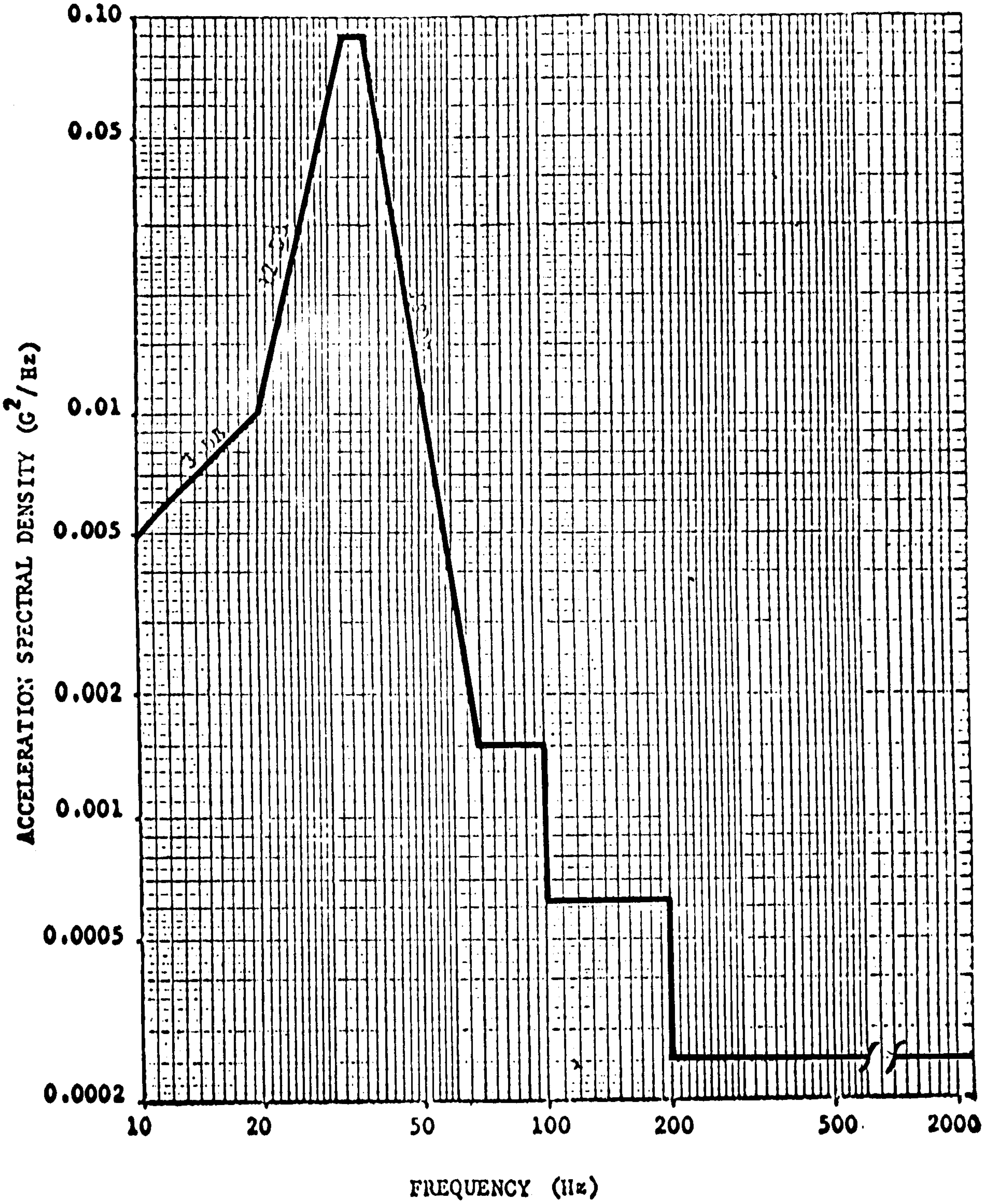


Figure 3b. Vibration Levels. Longitudinal. Stowed in Vehicle

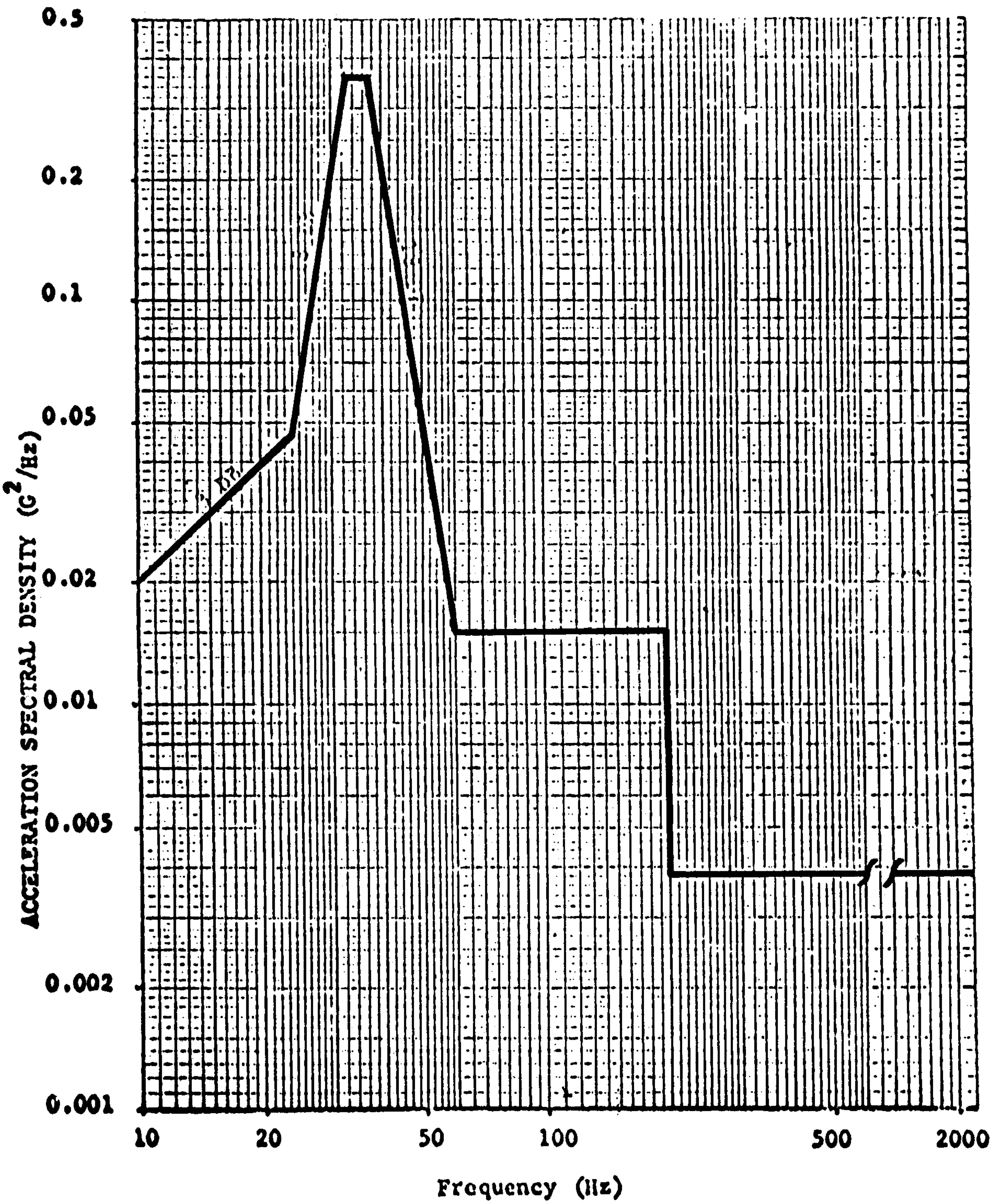


Figure 3c. Vibration Levels, Transverse,
Stowed in Vehicle

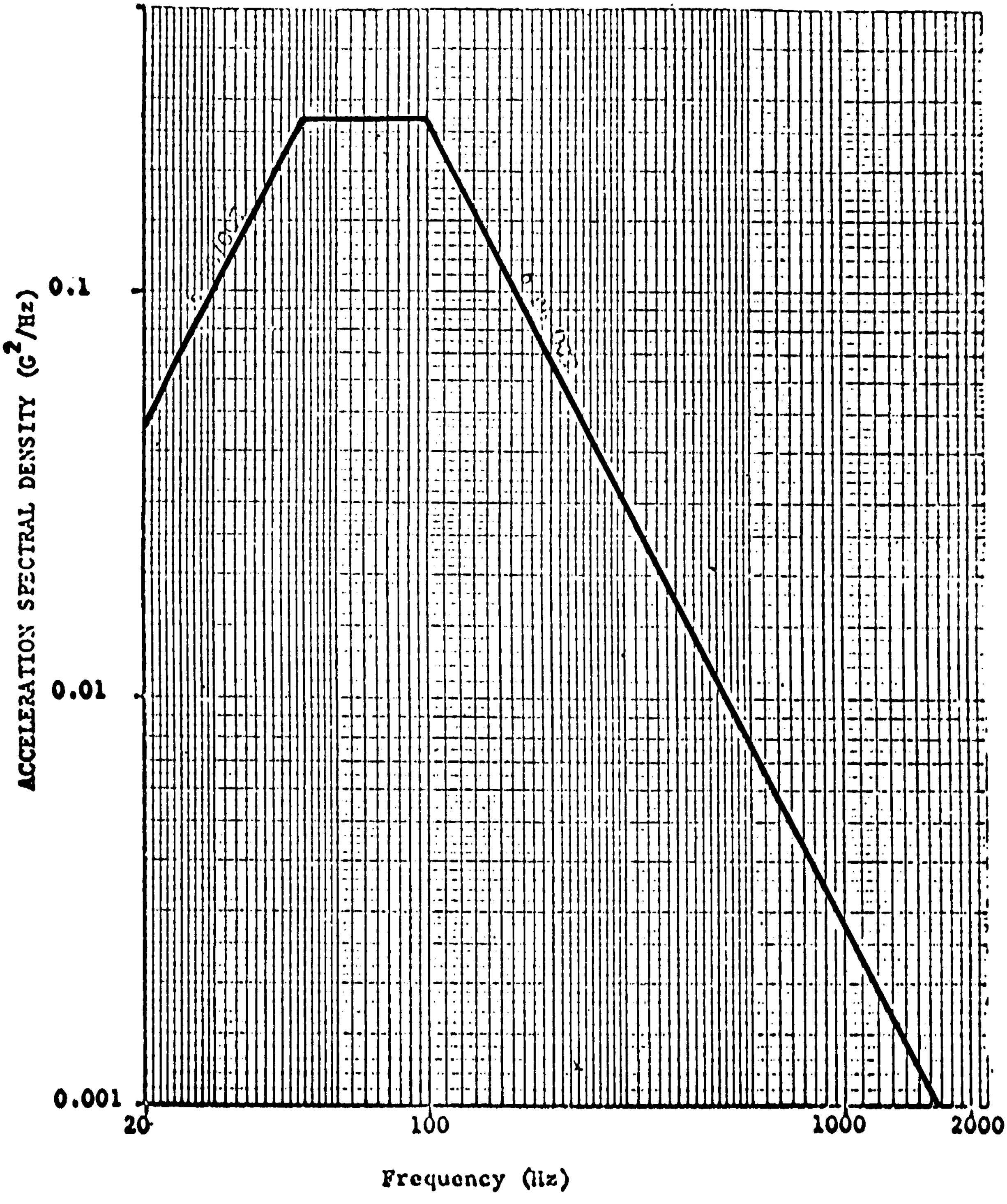


Figure 4a. Vibration Levels, Vertical. Deployed on Vehicle

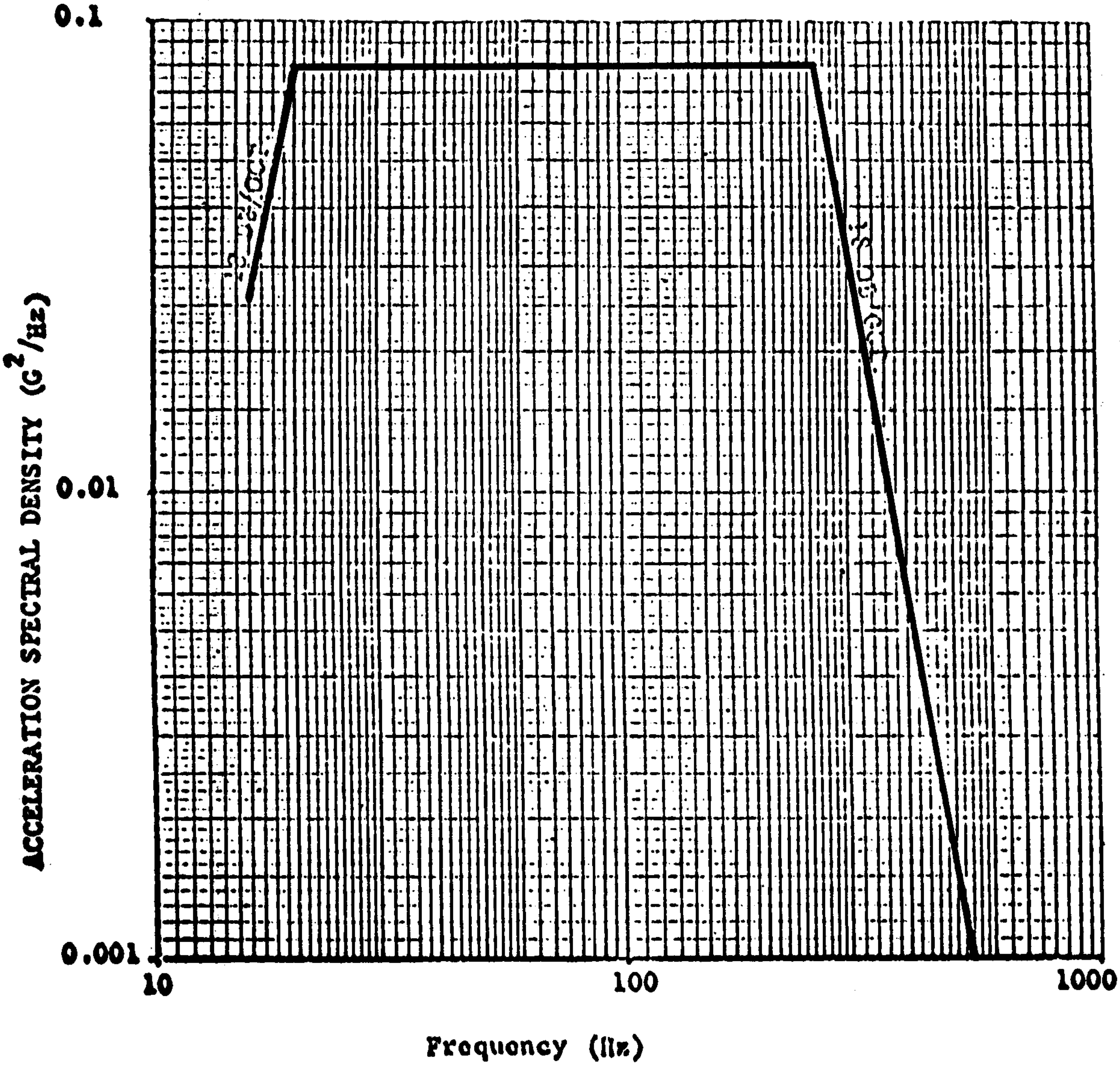


Figure 4b. Vibration Levels. Longitudinal Deployed on Vehicle[1]

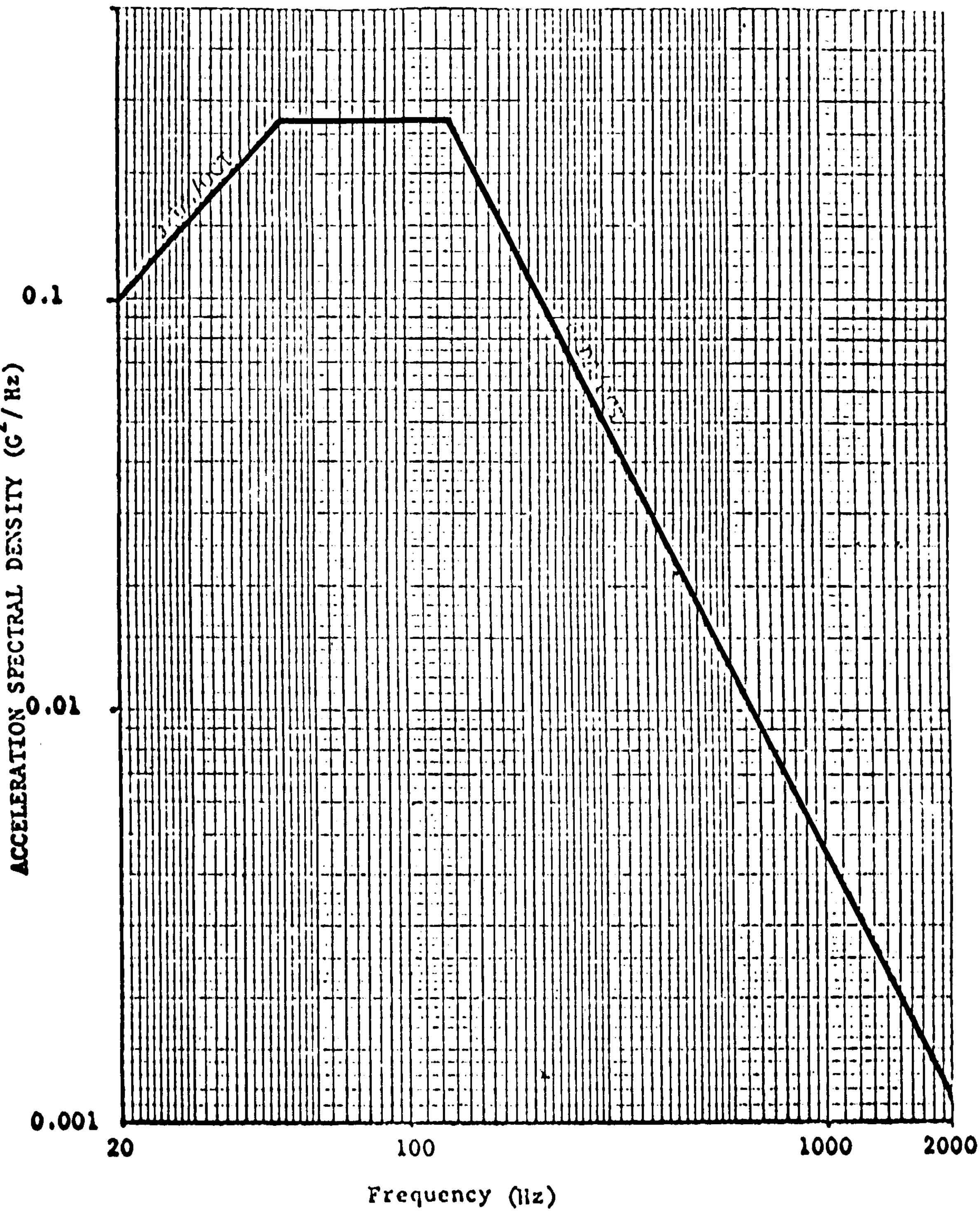


Figure 4c. Vibration Levels. **Transverse.**
Deployed on Vehicle

APPENDIX I (A)

DRAFT FOR FLAT CABLE CONNECTORS

CONNECTORS, ELECTRICAL, NON-ENVIRONMENT RESISTANT, FOR USE WITH FLEXIBLE FLAT CONDUCTOR CABLE AND ROUND WIRE, GENERAL SPECIFICATION FOR

1. SCOPE

1.1 Scope. This specification covers the general requirements for multi-contact non-environment-resistant, electrical connectors for use with flexible flat conductor cable and round wire. The technical requirements and tests are intended to enable evaluation of the general performance of connectors, which will meet the conditions encountered in military use.

1.2 Classification.

1.2.1 Military part number. The military part number shall be in the following form, and as specified (see 3.1).

M55544/1- $\underbrace{-----}$

Military specification number — Specification sheet number — See 3.1 for coded dash numbers

1.2.1.1 Contact category. The type of contact and insert, as applicable, shall be identified by a single letter (see 3.1).

1.2.1.2 Contact spacing. The nominal center-to-center spacing, in inches, between contacts is indicated by a single digit number representing 0.025 increments (see 3.1).

1.2.1.3 Cable width. The cable width, which each connector shall accommodate, shall be designated by a letter as specified (see 3.1).

1.2.1.4 Number of cable layers and shielding. A single digit (arabic numeral) shall denote the number of cable layers unshielded or shielded (see 3.1).

1.2.1.5 Key and keyway positions. Keying positions are denoted by a single letter (see 3.1).

3. REQUIREMENTS

3.1 Specification sheets. The individual item requirements shall be as specified herein and in accordance with the applicable specification sheets. In the event of any conflict between the requirements of this specification and the specification sheets, the latter shall govern.

3.2 Qualification. Connectors furnished under this specification shall be products which are qualified for listing on the applicable qualified products list at the time set for opening of bids (see 4.3).

3.3 Materials. The materials shall be as specified herein. However, when a definite material is not specified, a material shall be used which will enable the connector and accessories to meet the performance requirements. Certification that such material has met applicable requirements shall be forwarded by the supplier through the cognizant government inspection element for approval of the procuring activity. Acceptance or approval of any constituent material shall not be construed as a guaranty of the acceptance of the finished product.

3.3.1 Dissimil[illegible] [illegible] metals are used in intimate contact with each other, protection aga[illegible] [illegible]. Dissimilar metals are as defined in requirement 16 of MIL-S[illegible]

3.3.2 Material [illegible] specified herein or in the applicable specification sheet, all compon[illegible] shall be of a material to conform to the permeability requ[illegible]

3.3.3 Resilient ma[illegible] [illegible] and grommets, except for sealing plugs, shall be of a resilient dielectric material [illegible] the performance requirements as specified herein and the applicable specific[illegible] [illegible].

3.3.4 Plastic mat[illegible] [illegible] otherwise specified (see 3.1), plastic materials shall be of the highest grade and [illegible] commercially available, and shall conform to type SGD-F of MIL-M-14, or type GDI-30F of [illegible]

3.3.5 Shell mat[illegible] [illegible] otherwise specified, the shell shall be of a suitable high grade aluminum materia[illegible], [illegible] performance requirements specified herein and the applicable speci[illegible] [illegible].

3.3.5.1 Shell finis[illegible] [illegible] made of corrosion-resistant material shall be protected with a coating capable of m[illegible] performance requirements specified herein and the applicable specification sheet (see [illegible]). [illegible] type connectors shall be electrically conductive (see 3.5.2).

3.3.6 Contact m[illegible] [illegible] shall be made from a suitable conductive material capable of meeting the performa[illegible] requirements specified herein and the applicable specification sheet (see 3.1).

3.3.6.1 Contact finis[illegible] [illegible] contacts shall be gold-plated in accordance with type II, class I of MIL-G-45204 over a [illegible] underplate, except that silver underplate shall not be used.

3.4 Contacts and operating temperature.

3.4.1 Contacts. Pin and socket contact sizes and ratings shall be as specified in MIL-C-39029. Where flat cable conductor serves as a contact, the ratings shall be 3 amperes (amps) for 0.050 and 0.0750 inch spacings, and [illegible] for 0.100 inch spacing (see 3.1).

3.4.2 Operating temperature. Unless otherwise specified (see 3.1), connectors shall be capable of continuous operation over a temperature range of $-55°C$ to $105°C$.

3.5 Design and construction. Connectors shall be of the design, construction, and physical dimensions specified herein and the applicable specification sheet (see 3.1). Dimensions shall be in accordance with USASI Y14.5 - 1966.

3.5.1 Connector assembly. All parts of the wired connector assembly, particularly the contacts, shall not be displaced from their original normal fitted position at completion of the specified tests.

3.5.2 Shells. The shells shall be constructed to mechanically retain the inserts and protect them from damage. Shells for shielded connector types shall be capable of meeting the requirement for shielded termination where applicable. Electrically conductive mating shells shall be designed so that prior to engagement of the connector contacts, electrical continuity is effected through each mating half during mechanical mating.

3.5.3 Inserts. Inserts shall be of a suitable insulating material in accordance with 3.3.3 and 3.3.4, and be capable of meeting the performance requirements. Inserts shall have no voids and shall firmly retain the contacts.

3.5.4 Contacts. Connectors shall be so designed that contacts shall not be damaged during mating and unmating of counterpart connectors. Contacting surfaces shall be smooth and uniform, and shall include a wiping action during mating. The size of pin and socket contacts shall be as specified in MIL-C-39029. For various contact spacing, see 1.2.1.2.

3.5.4.1 Pin contacts. Pin contacts shall have nominal engaging end diameters as specified in MIL-C-39029.

3.5.4.2 Socket contacts. Size 23 and larger socket contacts shall be closed entry type and shall have a radius or be chamfered to direct and center the entering pin contact. Socket engaging bore diameters shall be as specified in MIL-C-39029.

3.5.4.3 Flat conductor cable contacts. Flat conductor cables used as direct contact surfaces shall be finished and assembled in accordance with the military standard drawing specified in the applicable specification sheet (see 3.1).

3.5.4.4 Round wire contacts. When individually removable contacts for round wire are used, they shall be inserted into and removed from the connector without damaging the insert or seal members. Insertion and removal may be accomplished with the aid of acceptable tools (see 3.1). Contacts shall accommodate the AWG wire sizes shown in MIL-C-39029.

3.5.4.5 Contact arrangement. Contact arrangements in inserts shall be as specified in the applicable specification sheet (see 3.1).

3.5.5 Seals. Seals shall be as specified in the applicable specification sheet (see 3.1).

3.5.5.1 Interfacial seals. Interfacial seals, when specified (see 3.1), shall be bonded to the mating face of the insert. All air paths between adjacent contacts and between contacts and shells shall be eliminated in mated connectors. There shall be interfacial mating of the engaged connector seals to provide dielectric under compression.

3.5.5.2 Wire and cable seals. Wire and cable seals shall be capable of sealing wires or cables at the back faces of the connector by resilient grommets or potting materials (see 3.1). Potting material not approved for Air Force use unless approved by the procuring activity.

3.5.6 Screw threads. Screw threads shall conform to MIL-S-7742 and Handbook H-28.

3.5.7 Cable strain relief. Connectors shall have suitable means to protect conductor terminations and contacts against pull and flexing forces (see 3.1).

3.5.8 Polarization. A polarization feature shall be part of each connector assembly to preclude mating in more than one position. Polarization shall be accomplished before engagement of electrical contacts (see 3.1).

3.5.9 Locking mechanism. A locking mechanism shall be provided for locking the plug into the receptacle to withstand service conditions without disconnecting (see 3.1).

3.6 Connector mating and unmating forces. Plugs and receptacles shall be capable of being mated and unmated without the aid of any special tool. The force required to both engage or separate any pair of connectors (plug and receptacle) shall not exceed the maximum force or torque as specified in the applicable specification sheets (see 3.1), when tested in accordance with 4.6.2.

3.7 Shell to shell continuity (shielded connectors only). The overall direct current (dc) resistance shall not exceed 0.25 ohm when tested as specified in 4.6.3 (see 3.1).

3.8 Insulation resistance. The insulation resistance shall be greater than 5,000 megohms when tested in accordance with 4.6.4.

3.8.1 Insulation resistance after high temperature exposure. Unless otherwise specified (see 3.1), the insulation resistance shall be greater than 50 megohms when tested in accordance with 4.6.4.1.

3.9 Dielectric withstanding voltage. Connectors shall show no evidence of breakdown of insulation or flashover when tested as specified in 4.6.5.

3.10 Cable retention (flat cable only). The retention feature of the connector shall withstand without slippage or mechanical damage, a minimum retention force of 25 pounds per-inch-of-cable-width applied axially (see 4.6.6).

3.11 Vibration. The connector assembly, completely wired and mated, shall show no evidence of cracks, breaks, or loosening of parts when tested as specified in 4.6.7. During this test the circuit, which incorporates the mated contacts of the connector, shall show no interruption in electrical continuity greater than one microsecond.

3.12 Salt spray (corrosion). There shall be no pitting, peeling, chipping, or blistering of metal surfaces, or exposure of base metal when tested as specified in 4.6.8.

3.13 Contact retention (pin and socket connector only). Pins and sockets which are inserted or molded into the connector insert and locked into position (see 3.1), shall each withstand an axial load as specified in table I. There shall be no damage to the contact, insert, or connector body, or to the contact retention system when tested in accordance with 4.6.9.

TABLE I. Axial loads for individual contact retention.

Contact size	Min retention force (pounds)
20	15
22, 23	10
24	5

3.14 Connector-cable flexing capability (flat cable only). The connectors shall be tested in accordance with 4.6.10 while under a tension of 2 ±.1 lbs/in. of cable-width. There shall be no evidence of partial, intermittent or complete shorting between conductors during and after this test. There shall be no evidence of discontinuity of one microsecond or greater between conductors during and after this test. There shall be no flaws or damage resulting from the tests.

3.15 Durability. Plugs, receptacles and latching hardware shall show no mechanical or electrical defects detrimental to the operation of the connector, after 500 cycles of mating and unmating in accordance with 4.6.11.

3.16 Contact resistance. Unless otherwise specified in the applicable specification sheet (see 3.1), the individual millivolt (mV) drop shall be in accordance with MIL-C-39029 when tested in accordance with 4.6.12.

3.16.1 Low level contact resistance. Unless otherwise specified in the applicable specification sheet (see 3.1), the low level contact resistance shall not exceed the values specified in MIL-C-39029, when tested as specified in 4.6.12.1.

3.17 Thermal shock. There shall be no evidence of cracking, crazing, or other physical damage to the connector assembly when tested as specified in 4.6.13. The connectors shall be capable of being manually mated and unmated at the extreme low temperature.

3.18 Shock (specified pulse). When tested as specified in 4.6.14, there shall be no physical damage to the connector assembly. During this test the circuit, which incorporates the mated contacts of the connector, shall show no interruption in electrical continuity greater than one microsecond.

3.19 Moisture resistance. Mated connectors shall maintain an insulation resistance (see 4.6.4) of 100 megohms or greater at 25° C, and a relative humidity of 90-98 percent, and 5,000 megohms or greater after conditioning for 24 hours at room ambient temperature and humidity (see 4.6.15).

3.22 Altitude immersion. After subjection to the altitude immersion test specified in 4.6.16, and unless otherwise specified in the applicable specification sheet (see 3.1), connectors shall have an insulation resistance of not less than 1,000 megohms and shall show no evidence of breakdown or flashover when subjected to the dielectric withstanding voltage test of 4.6.5.1. Mating to be maintained by normal means.

3.23 Permeability. When measured as specified in 4.6.17, the relative permeability (mu) of the connector shall be no greater than 2.0.

3.24 Sand and dust. Connectors shall meet the requirements for insulation resistance and contact resistance as specified in 3.8 and 3.16, respectively, after exposure to sand and dust as specified in 4.6.18.

3.25 Ozone. Connectors shall show no evidence of cracking of materials and shall meet the requirements for insulation resistance as specified in 3.8 after exposure to ozone as specified in 4.6.19.

3.26 Fungus. Connectors shall be fungus-free when tested as specified in 4.6.20.

3.27 Life (at elevated ambient temperature). Connectors shall meet the requirements for insulation resistance and low level contact resistance as specified in 3.8 and 3.16.1, respectively, after the temperature life conditioning as specified in 4.6.21.

3.29 Interchangeability. Receptacles of a given type shall be capable of being mated with associated plugs meeting the requirements of this specification and the applicable specification sheets. The mated connectors and individual plugs and receptacles having part numbers shall be directly and completely interchangeable with each other with respect to installation and performance as specified herein, and the applicable specification sheet (see 3.1 and 4.6.22).

3.30 Marking. All marking shall be in accordance with MIL-STD-130. The marking shall remain legible after completion of the tests specified herein.

3.30.1 Connectors. Connectors and accessories shall be marked with the military part number (see 1.2.1), the supplier's name or code symbol, and the date code as specified in MIL-STD-1285. Marking shall be located on an accessible external surface on the connector and accessories.

3.30.2 Contact identification. Contact positions shall be permanently identified by legible numbers and letters applied on the connector as specified in the applicable specification sheet (see 3.1).

3.31 Workmanship. Connectors and accessories shall be processed in such a manner as to be uniform in quality and shall be free from burrs, crazing, cracks, voids, pimples, chips, blisters, pinholes, sharp cutting edges, and other defects that will affect life, serviceability, or appearance.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for inspection. Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified in the contract or order, the supplier may use his own or any other facilities suitable for the performance of the inspection requirements specified herein, unless disapproved by the government. The government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

4.1.1 Test equipment and inspection facilities. Test and measuring equipment and inspection facilities of sufficient accuracy, quality and quantity to permit performance of the required inspection shall be established and maintained by the supplier. The establishment and maintenance of a calibration system to control the accuracy of the measuring and test equipment shall be in accordance with MIL-C-45662.

4.2 Classification of inspection. The examination and testing of connectors and associated fittings shall be classified as follows:

(a) Qualification inspection (see 4.4).
(b) Quality conformance inspection (see 4.5).

4.3 Inspection conditions. Unless otherwise specified herein, all inspections shall be performed in accordance with the test conditions specified in the "GENERAL REQUIREMENTS" of MIL-STD-202.

4.4 Qualification inspection. Qualification inspection shall be performed at a laboratory acceptable to the government (see 6.3), on sample units produced with equipment and procedures normally used in production.

4.4.1 Sample size. The number and types of sample plugs and receptacles to be submitted for qualification shall be as specified in the appendix to this specification. The samples shall be produced with equipment and procedures normally used in production. The sample pairs shall be consecutively numbered.

TABLE II. Qualification inspection.

Examination or test	Requirement paragraph	Method paragraph
Group I - All sample units		
Visual and mechanical examination	3.1, 3.3, 3.5, 3.29, 3.30, and 3.31	4.6.1, 4.6.25
Connector mating and unmating forces	3.6	4.6.2
Shell to shell continuity (shielded connectors only)	3.7	4.6.3
Insulation resistance	3.8	4.6.4
Dielectric withstanding voltage (sea level)	3.9	4.6.5.1
Cable retention (flat cable only)	3.10	4.6.6
Group II 1/		
Dielectric withstanding voltage (high altitude)	3.9	4.6.5.2
Vibration, high frequency	3.11	4.6.7
Salt spray (corrosion)	3.12	4.6.8
Contact retention	3.13	4.6.9
Connector-cable flexing capability	3.14	4.6.10
Durability	3.15	4.6.11
Insulation resistance	3.8	4.6.4
Contact resistance	3.16	4.6.12
Group III		
Thermal shock	3.17	4.6.13
Insulation resistance after high temperature exposure	3.8.1	4.6.4.1
Shock (specified pulse)	3.18	4.6.14
Moisture resistance	3.19	4.6.15
Contact resistance	3.16	4.6.12
Group IV		
Durability 2/	3.15	4.6.11
Thermal shock	3.17	4.6.13
Air leakage	3.20	4.6.16
Water immersion	3.21	4.6.17
Altitude immersion	3.22	4.6.18
Contact resistance	3.16	4.6.12
Group V		
Contact resistance	3.16	4.6.12
Permeability	3.23	4.6.19
Sand and dust	3.24	4.6.20
Ozone	3.25	4.6.21
Fungus	3.26	4.6.22
Life (at elevated ambient temperature)	3.27	4.6.23
Group VI		
Fluid immersion	3.28	4.6.24

1/ For number of sample units to be tested for each group, see appendix.

2/ 30 cycles of mating and unmating.

4.4.2 Inspection routine. The qualification tests shall consist of all the tests specified herein and shall be performed in the order shown in table II. All sample units shall be subjected to the tests specified in group I. The sample units shall then be divided as specified in the appendix. After the visual and mechanical examination in group I, the connectors shall be fabricated with three-foot lengths of flat conductor cable in accordance with , or three-foot lengths of type E teflon coated wire conforming to MIL-W-16878. The conductor or the wire size shall be the same size as the contact size, except that the sample pairs for group IV testing shall have the cable or wire 6 ±.5 inches long, measured from the face of the connector to the end of the cable or wire.

4.4.3 Failures. Failure of any one of the tests in table II shall be cause for refusal to grant qualification. All failures shall be attributed to the connector unless data is provided showing failure is due to the cable or test fixture.

4.4.4 Retention of qualification. To retain qualification, the supplier shall forward a report at 12-month intervals to the qualifying activity. The qualifying activity shall establish the initial reporting date. The report shall consist of:

(a) A summary of the results of the tests performed for inspection of product for delivery (groups A and B), indicating as a minimum the number of lots that have passed and the number that have failed. The results of tests of all reworked lots shall be identified and accounted for.

(b) A summary of the results of tests performed for qualification verification inspection, (group C), including the number and mode of failures. The summary shall include results of all qualification verification inspection tests performed and completed during the 12-month period. If the summary of the test results indicates nonconformance with specification requirements, and corrective action acceptable to the qualifying activity has not been taken, action may be taken to remove the failing product from the qualified products list.

Failure to submit the report within 30 days after the end of each 12-month period may result in loss of qualification for the product. In addition to the periodic submission of inspection data, the supplier shall immediately notify the qualifying activity at any time during the 12-month period that the inspection data indicates failure of the qualified product to meet the requirements of this specification.

In the event that no production occurred during the reporting period, a report shall be submitted certifying that the company still has the capabilities and facilities necessary to produce the item. If during 2 consecutive reporting periods there has been no production, the manufacturer may be required, at the discretion of the qualifying activity, to submit (the products, a representative product of each type, grade, class, etc.) to testing in accordance with the qualification inspection requirements.

4.5 Quality conformance inspection.

4.5.1 Inspection of product for delivery. Inspection of product for delivery shall consist of groups A and B inspection.

4.5.1.1 Inspection lot. An inspection lot may consist of all the connectors, counterpart receptacles and plugs as indicated in each specification sheet, produced under essentially the same conditions and offered for inspection at one time. When only the plug or receptacle is specified in the contract or order, the manufacturer shall supply the counterpart receptacle or plug for inspection purposes.

4.5.1.2 Group A inspection. Group A inspection shall consist of the examinations and tests specified in table III and shall be made on the same set of sample units in the order shown. The sample units may be wired or unwired at the option of the supplier. If unwired samples are submitted, the test apparatus shall meet prior government approval.

4.5.1.2.1 Sampling plan. Statistical sampling and inspection shall be in accordance with MIL-STD-105 for general inspection, and the acceptable quality level (AQL) shall be as specified in table III. Major and minor defects shall be as defined in MIL-STD-105.

TABLE III. Group A inspection.

Examination or test	Requirement paragraph	Method paragraph	AQL (percent defective) Major	Minor
Visual and mechanical examination - - -	3.1, 3.3, 3.5, 3.30 and 3.31	4.6.1	1.0	4.0
Electrical				
Insulation resistance - - - - - - - - - -	3.8	4.6.4	1.0	1/
Dielectric withstanding voltage - - - - - - - - - - - - - - - -	3.9	4.6.5.1		

1/ All electrical defects are considered major defects.

4.5.1.2.2 Rejected lots. If an inspection lot is rejected, the supplier may rework it to correct the defects, or screen out the defective units, and resubmit for reinspection. Resubmitted lots shall be inspected using tightened inspection. Such lots shall be separate from new lots, and shall be clearly identified as reinspected lots.

4.5.1.2.3 Disposition of sample units. If the lot is accepted, unwired samples may be delivered on the contract or order. The wired samples with removable contacts may be delivered on the contract or order provided the wired contacts are replaced with new contacts.

4.5.1.3 Group B inspection. Group B inspection shall consist of the tests specified in table IV, in the order shown, and shall be made on sample units which have been subjected to and have passed the group A inspection.

4.5.1.3.1 Sampling plan. The sampling plan shall be in accordance with MIL-STD-105 for special inspection level S-3. The sample size shall be based on the inspection lot size from which the sample was selected for group A inspection. The AQL shall be as shown in table IV.

4.5.1.3.1.1 Preparation of sample units. All connector samples shall be wired after the interchangeability test with cable or wire 6 inches (minimum) long measured from the face of the connector to the end of the wire or cable.

4.5.1.3.2 Rejected lots. If an inspection lot is rejected, the supplier may rework it to correct the defects, or screen out the defective units, and resubmit for reinspection. Resubmitted lots shall be inspected using tightened inspection. Such lots shall be separate from new lots, and shall be clearly identified as reinspected lots.

TABLE IV. Group B inspection.

Examination or test	Requirement paragraph	Method paragraph	AQL % Def.
Interchangeability	3.29	4.6.25	2.5
Connector mating and unmating forces	3.6	4.6.2	2.5
Shell to shell continuity (shielded connectors)	3.7	4.6.3	
Cable retention (flat cable only)	3.10	4.6.6	
Contact retention	3.13	4.6.9	
Contact resistance	3.16	4.6.12	
Thermal shock	3.17	4.6.13	2.5
Air leakage	3.20	4.6.16	
Water immersion	3.21	4.6.17	
Altitude immersion	3.22	4.6.18	

4.5.1.3.3 Disposition of sample units. Sample units which have been subjected to group B inspection shall not be delivered on the contract or order.

4.5.2 Qualification verification inspection. Qualification verification inspection shall consist of group C. Except where the results of these inspections show noncompliance with the applicable requirements (see 4.5.2.1.4), delivery of products which have passed groups A and B shall not be delayed pending the results of these qualification verification inspections.

4.5.2.1 Group C inspection. Group C inspection shall consist of the tests specified in table V, in the order shown. Group C inspection shall be made on sample units selected from inspection lots which have passed the groups A and B inspection.

4.5.2.1.1 Sampling plan. For group C inspection, 6 mated pairs, plus one plug and one receptacle for each connector tested in each fluid (see 3.1), representing each qualification combination (see 20.1 and 20.2) shall be selected at random from units produced 12 months from date of qualification, and every 12 months thereafter. The sample connectors selected shall be of the widest width and maximum number of contacts produced during this period. Counterpart plugs or receptacles shall be supplied by the manufacturer when necessary for inspection purposes. The first sample units shall be selected at the start of the contract from the first inspection lot. Two mated sample connectors shall be subjected to each subgroup in table V, except that one plug and one receptacle shall be used for each connector tested in each fluid (see 3.1), in subgroup IV.

4.5.2.1.2 Failures. If one or more sample units fail to pass group C inspection, the entire lot shall be considered to have failed.

4.5.2.1.3 Disposition of sample units. Sample units which have been subjected to group C inspection shall not be delivered on the contract or order.

TABLE V. Group C inspection.

Test	Requirement paragraph	Method paragraph
Subgroup I		
Dielectric withstanding voltage (high altitude)	3.9	4.6.5.2
Vibration, high frequency	3.11	4.6.7
Salt spray (corrosion)	3.12	4.6.8
Connector-cable flexing capability	3.14	4.6.10
Durability	3.15	4.6.11
Insulation resistance	3.8	4.6.4
Contact resistance	3.16	4.6.12
Subgroup II		
Thermal shock	3.17	4.6.13
Insulation resistance after high temperature exposure	3.8.1	4.6.4.1
Shock (specified pulse)	3.18	4.6.14
Moisture resistance	3.19	4.6.15
Subgroup III		
Permeability	3.23	4.6.19
Sand and dust	3.24	4.6.20
Ozone	3.25	4.6.21
Fungus	3.26	4.6.22
Life (at elevated ambient temperature)	3.27	4.6.23
Low level contact resistance	3.16.1	4.6.12.1
Subgroup IV		
Fluid immersion	3.28	4.6.24

4.5.2.1.4 Noncompliance. If a sample unit fails to pass group C inspection, the supplier shall take corrective action on the material or processes or both, as warranted, and on all units of product which can be corrected and which were manufactured under essentially the same conditions, with essentially the same materials, processes, etc., and which are considered subject to the same failure. Acceptance of the product shall be discontinued until corrective action, acceptable to the government has been taken. After the corrective action has been taken, group C inspection shall be repeated on additional sample units (all inspections or the inspection that the original sample failed, at the option of the government). Groups A and B inspection may be reinstituted; however, final acceptance shall be withheld until the group C reinspection has shown that the corrective action was successful. In the event of failure after reinspection, information concerning the failure and the corrective action taken shall be furnished to the cognizant inspection activity and the qualifying activity.

4.6 Methods of examination and test.

4.6.1 Visual and mechanical examination. The connectors, accessories, and piece parts shall be visually and mechanically examined to ensure conformance with this specification and the applicable specification sheets (see 3.1, 3.3, 3.5, 3.29, 3.30 and 3.31).

4.6.2 Connector mating and unmating forces (see 3.6). The wired plug and receptacle shall be mated and unmated as specified in (a) below. A locking mechanism (jackscrew, clips, etc.) shall not be used. There shall be no mating of the connector after manufacture for conditioning purposes, prior to the test. Each plug and receptacle so mated, shall be considered as one test sample unit where further testing of the plug or receptacle is indicated. The test procedure and measuring equipment shall conform to the following:

(a) The speed of insertion of the plug into the receptacle contacts shall not exceed 2 inches per minute for constant speed machines, or the rate of loading shall not exceed 80 pounds per minute for constant-rate-of-force machines.
(b) Scale mechanisms shall have no dashpots or other damping devices.
(c) Scales shall be calibrated in 1/8-pound steps or less, and shall be accurate to within 1/8-pound.

4.6.3 Shell to shell continuity (see 3.7). The dc resistance of the wired, mated, assembled connectors shall be measured between the rear end of the plug and the front face of the receptacle flange. The applied potential shall be 1.5 volts dc maximum. A resistance shall be inserted in the circuit to limit the current to 0.100 ±0.010 amperes. A probe with a spherical end of 0.05 inch minimum shall be used to make the voltage measurements on the receptacles. The probe shall not puncture or otherwise damage the connector.

4.6.4 Insulation resistance (see 3.8). Unless otherwise specified, unmated wired connectors shall be tested in accordance with method 302 of MIL-STD-202. Unmated connectors may be unwired for initial quality conformance inspection, provided the test apparatus meets prior government approval. The following details and conditions shall apply:

(a) Test condition - A
(b) Points of measurement - Between at least 3 adjacent pairs of contacts and between the shell and 2 adjacent contacts. The contacts selected shall be those having the closest spacing between measurement points.

4.6.4.1 Insulation resistance after high temperature exposure (see 3.8.1). The insulation resistance shall be measured in accordance with 4.6.4, except that the unmated, wired connectors shall have been exposed to an ambient temperature of +125° C ± 5° for 30 minutes. The measurements shall be made at the end of 500 hours while the connectors are at elevated temperature.

4.6.5 Dielectric withstanding voltage (see 3.9). Connectors shall be tested in accordance with method 3001 of MIL-STD-1344. The following details shall apply;

(a) Special conditions - As specified (see 3.1).
(b) Magnitude of test voltage - as specified in Table VI
(c) Duration of application of test voltage- For a period of 1 minute, unless otherwise specified (see 3.1).
(d) Points of application of test voltage - Between current carrying parts and ground, unless otherwise specified (see 3.1). On multiple-contact connectors, the voltage shall be applied between all contacts alternately connected.

TABLE VI. Test voltage.

Contact center spacing (inches)	Voltage at 60 cycles rms
0.050	800
0.075	1,500
0.100	2,000

4.6.6 Cable retention (flat cable only). The unmated wired connector shall be mounted by normal mounting means and alined with the test fixture. An axial force as specified in 3.10 shall be applied uniformly across the width of the cable. The force shall be applied 6 inches from the mating face of the connector to each cable separately and shall pull away from the connector.

4.6.7 Vibration (see 3.1). Connectors shall be tested in accordance with method 2005 of MIL-STD-1344. The following details shall apply:

(a) Test condition number I.
(b) Measurement during test - Connectors shall be monitored for electrical continuity during the test. Equipment shall be sufficiently sensitive to detect any interruption with a duration of 10 microseconds.
(c) Test after vibration - Insertion and withdrawal and contact resistance shall be measured as specified in 4.6.11 and 4.6.12, respectively.

4.6.8 Salt spray (corrosion) (see 3.12). Connectors shall be tested in accordance with method 1001 of MIL-STD-1344. The following details shall apply:

(a) Test-condition letter- B of method 101, MIL-STD-202.
(b) Measurements after exposure - Immediately after exposure, connectors shall be washed with tap water and allowed to dry for 6 hours maximum in a circulating air oven at a temperature of 38° ± 3° C. After drying, contact resistance shall be measured as specified in 4.6.12.

4.6.9 Contact retention (pin and socket connectors only). An axial load applied from the front, as specified in table I shall be applied to each contact on the mating end of the contact for a minimum period of 5 seconds. The contacts shall meet the requirements of 3.13.

4.6.10 Connector-cable flexing capability (flat cable only). The assembled wired connector shall be installed in a fixture. Each cable shall be gripped 12 inches from the connector with an applied tension of 2 ±.1 pounds per-inch-of-cable-width per cable. Each cable shall be individually loaded. The cable or the connector shall be moved through an arc of 140 ±10 degrees for 200 cycles using either method 1 or 2 of figure 1. One complete cycle shall consist of the rotation of the cable or connector from the neutral position to 70 ±5 degrees in both directions. The cycling rate shall be 10 ±1 cycles per minute. A monitoring current of 10 mA shall be applied through the conductor of the test cables and the contacts of the connector in series. Either a dummy plug or receptacle or the actual test counterpart connector may be mated to the connector under test to facilitate making the series circuit. Suitable equipment shall be employed to monitor the current flow and to indicate a discontinuity of one microsecond interruption of current flow. After the completion of 200 cycles, a visual inspection shall be made to check for flaws or damage and the dielectric withstanding voltage shall be measured as specified in 4.6.5.1 (see 3.14).

4.6.11 Durability. Wired counterpart connectors and locking devices shall be mated and unmated 200 times in a manner to simulate actual service. A suitable lubricant may be used on the latching hardware. Upon completion of the specified cycling, the plug, receptacle, and latching hardware shall meet the requirements of 3.15.

4.6.12 Contact resistance (see 3.16). The contact resistance of the mated, wired connectors shall be measured at 25° ±3°C and at the maximum operating temperature (see 3.1). Measurements shall be taken after the temperature of the connector has stabilized. The contact resistance shall be tested in accordance with method 307 of MIL-STD-202 and MIL-C-39029 as applicable, except that the distance between measuring points shall be 6 ±.5 inches (see figure 2) and the number of test activations shall be one.

4.6.12.1 Low level contact resistance. The low level contact resistance test shall be performed using a circuit as shown on figure 3, or using one, which will deliver one mA current when the variable resistor (R_1) is adjusted to provide a 20 mV open circuit potential between T_1 and T_2. The wired mated connectors shall be rigidly mounted to a fixture to provide mechanical stability and shall be wired as in 4.5.13 above. Measurements shall be performed with direct current. A careful measurement of voltage drops across the contacts in both directions, while carrying a known current, will yield the parameters necessary to determine contact resistance. The contact resistance shall be calculated, in each, the forward and reverse direction, by dividing the voltage drop reading by the current reading and the higher of the two resistance values thus obtained for each contact shall not exceed the maximum allowable contact resistance, mV drop, as specified in 3.16.1. If the total resistance between points T_1 and T_2 exceeds 0.1 ohm (0.1 mV drop), the total number of contacts in series should be reduced for accurate readings.

4.6.13 Thermal shock (see 3.17). Connectors with unwired test probes inserted into contact sockets shall be tested in accordance with method 1003 of MIL-STD-1344. The following details shall apply:

(a) Test condition letter-B of method 107, MIL-STD-202 (or C, when specified (see 3.1).

(b) Examination after test - Connectors shall be visually examined for evidence of physical damage.

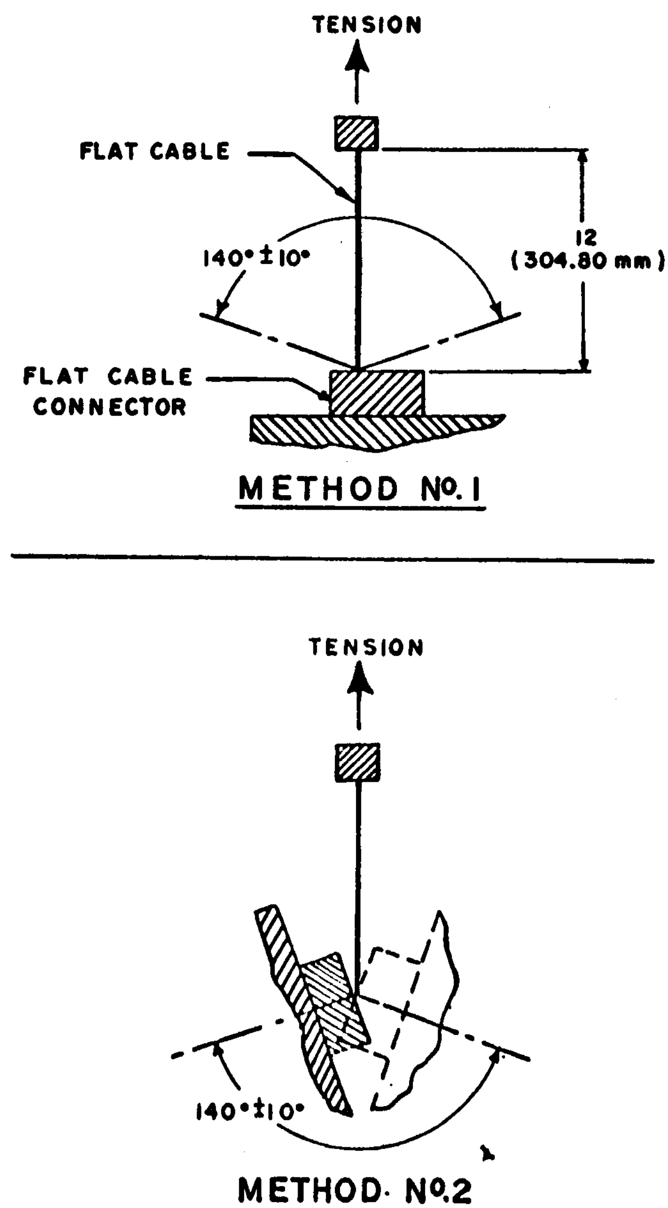


FIGURE 1. Cable flexing methods.

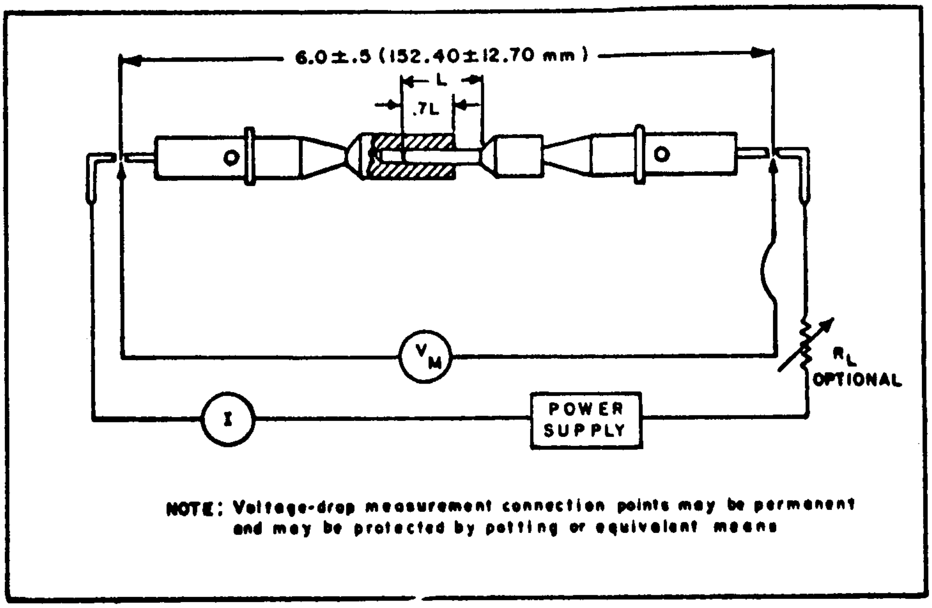
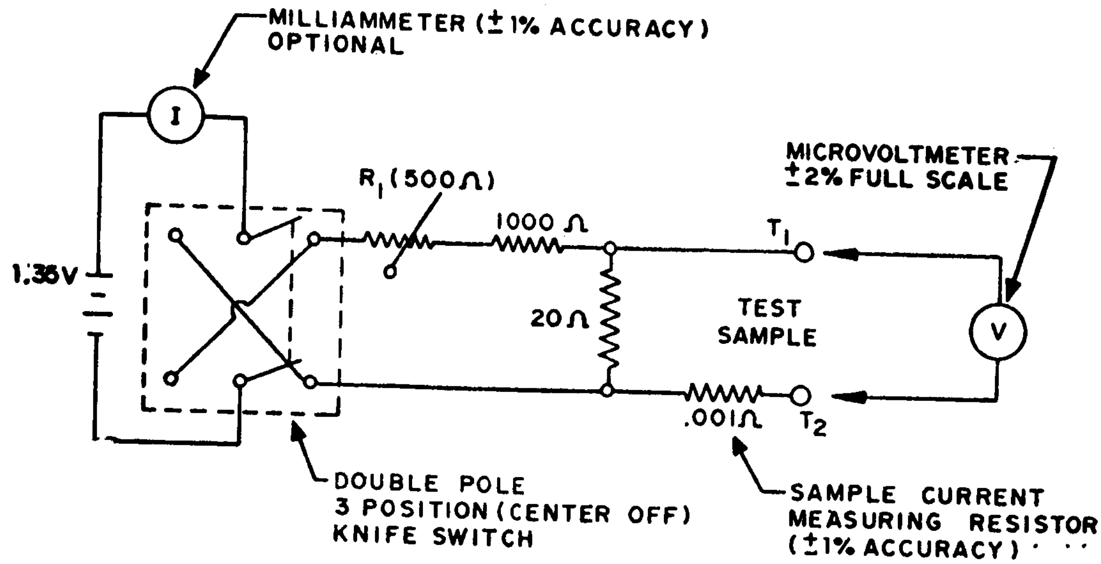
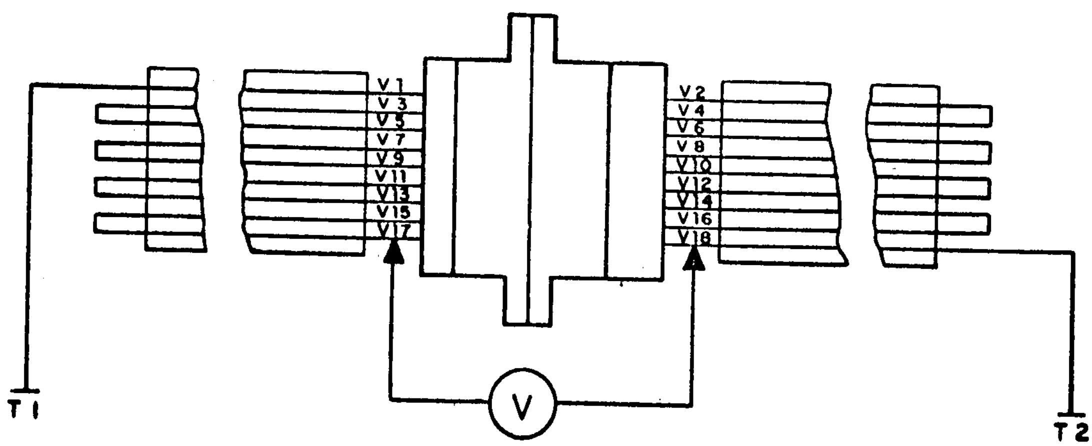


FIGURE 2. Test circuit for measurement of contact resistance.





NOTE: — VOLTAGE DROP MEASUREMENT CONNECTION POINTS V1, V2, ETC, MAY BE PERMANENT CONNECTIONS AND MAY BE PROTECTED BY POTTING OR EQUIVALENT MEANS.

FIGURE 3. Test circuit for measurement of low level contact resistance.

4.6.14 Shock (specified pulse) (see 3.18). Connectors, properly mated, shall be tested in accordance with method 2004 of MIL-STD-1344. The following details and exception shall apply:

(a) Mounting method - By normal mounting means on the shock-device or carriage. Plugs shall be engaged with the receptacles and held by normal locking means only. The wire bundles or cables shall be clamped to structures that move with the connectors. 8 ± .5 inches of wire or cable shall be unsupported behind the rear of each connector.

(b) Test condition letter - I of method 213, MIL-STD-202.
(c) Measurements during shock test - Connectors shall be monitored for electrical continuity both during and after the test. Loss of continuity for a period of longer than 10 microseconds constitutes a failure. During and after the test, the connectors shall meet the requirements specified in 3.18.

4.6.15 Moisture resistance (see 3.19). The wired, mated connectors shall be tested in accordance with method 106 of MIL-STD-202. The following details and exceptions shall apply:

(a) Mounting - Connectors shall be mounted within the chamber in a horizontal position with the cable or wire descending into the back shell with a minimum 2-inch bend radius. There shall be no drip loops or splices in the cable or wire.
(b) Steps 7a and 7b shall be omitted.
(c) After completion of step 6 of the final cycle and while still at high humidity, and mated, the insulation resistance shall be measured in accordance with 4.6.4.
(d) Following the measurement at high humidity, the wired, mated connectors shall be conditioned for 24 hours at room ambient temperature and humidity. The insulation resistance shall be measured in accordance with 4.6.4.

4.6.16 Altitude immersion (see 3.22). The wired, assembled, and mated connector shall be submerged in a water bath of 5 percent by weight salt solution. The ends of the wire or cable shall not be submerged. The solution container, with the submerged connector, shall be placed in an altitude chamber. The chamber pressure shall be reduced to a pressure level of one inch of mercury and maintained for at least 30 minutes. The chamber pressure shall then be returned to the standard atmospheric pressure in less than one minute. The connector shall remain submerged at standard atmospheric pressure for at least 15 minutes. This cycle shall be repeated two additional times for a total of 3 cycles. While submerged, the insulation resistance and dielectric withstanding voltage shall be measured as specified in 4.6.4 and 4.6.5.1, respectively.

4.6.17 Permeability. The permeability of the assembled connector shall be measured with an indicator conforming to MIL-I-17214 (see 3.23).

4.6.18 Sand and dust. Unless otherwise specified (see 3.1), the unmated, wired connectors shall be tested in accordance with method 110 of MIL-STD-202. The following details shall apply:

(a) Test condition - A.
(b) Measurements - After completion, the connectors shall meet the requirements of 3.24.

4.6.19 Ozone. The wired, assembled, unmated connectors shall be subjected to ozone having a concentration from 0.010 to 0.015 percent by volume for 2 hours at room temperature. At the end of the specified period, the connectors shall meet the requirements of 3.25.

4.6.20 Fungus (see 3.26). The unmated, wired connectors shall be subjected to a fungus resistant test in accordance with method 508 of MIL-STD-810. Submission of certification that materials used are fungus-inert will be considered compliance with the requirements specified herein without testing for fungus.

4.6.21 Life (at elevated ambient temperature) (see 3.27). The wired mated connectors shall be tested in accordance with method 108 of MIL-STD-202. The following details and exceptions shall apply:

(a) Temperature measurements shall be made on the shell of the connector. When more than one connector assembly is being tested at the same time in one oven, the temperature shall be monitored on at least two assemblies.
(b) A circulating air oven shall be used.
(c) Test temperature - $105^{\circ}\,{}^{+5^{\circ}}_{-0^{\circ}}$C
(d) Test condition - C.
(e) Measurements - After exposure, the connectors shall be stabilized at ambient temperature. The insulation resistance and low level contact resistance shall be measured as specified in 4.6.4 and 4.6.12.1, respectively.

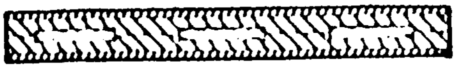
4.6.22 Inspection for interchangeability. The dimensions indicated below shall be gaged or measured to determine conformance to the physical interchangeability requirements of 3.29. When a listed dimension is not within specified design limits it shall be considered a major defect.

(a) External and internal dimensions of shells, covers, and insertable assemblies, when such dimensions affect mating parts.
(b) Dimensions of cavities, when such dimensions affect insertion of items.
(c) Location of connectors, locking pins, fasteners, slides and mountings, as applicable, which receive mating parts of plug-in assemblies and major units; and location of the mating parts on the plug-in assembly or major unit.

APPENDIX II

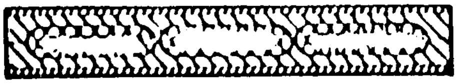
Flat Cable Designs

Using Flat Conductors

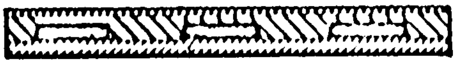


LAMINATED

EXTRUDED

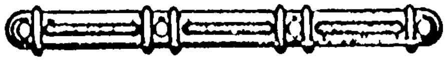


CONDUCTORS—PREINSULATED & LAMINATED



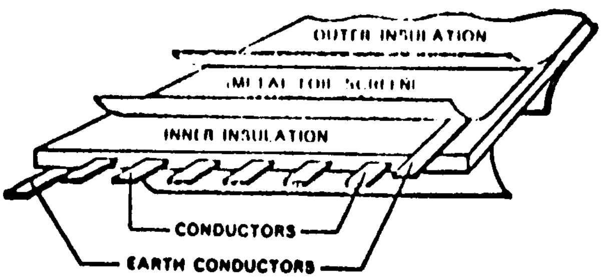
COATED COPPER – ETCHED & LAMINATED

COATED COPPER – ETCHED & SPRAYCOATED



WOVEN

Screening (Shielding)

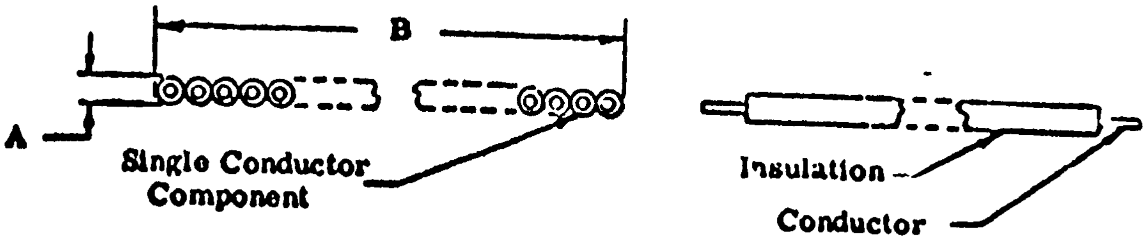


EFFECTIVELY SCREENED CONDUCTORS

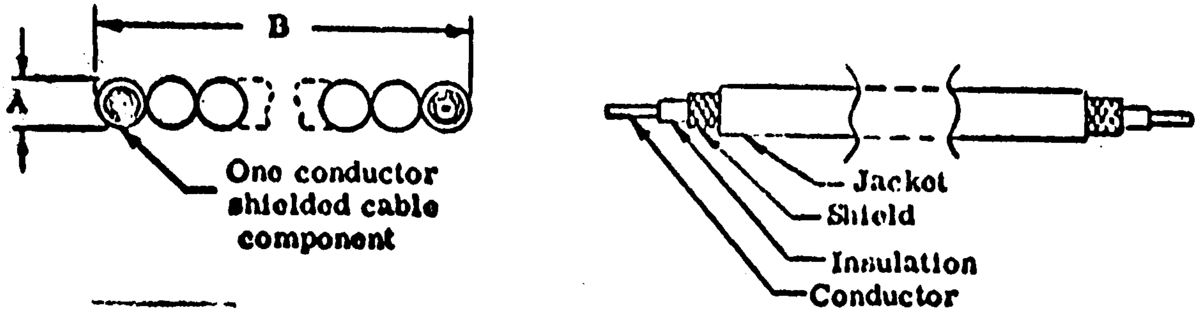
Copper foil and earth or ground wires sealed in the plastic insulation, effectively screen the conductors.

Using Round Conductors

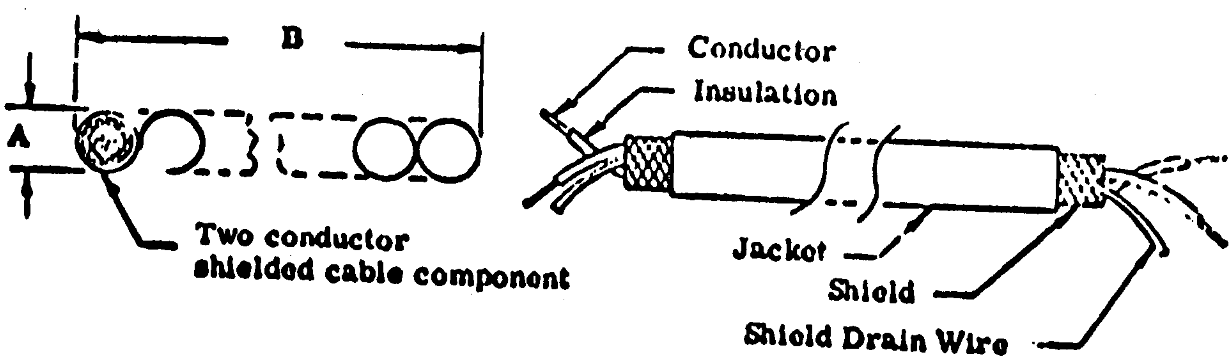
Multiple Single Conductor Flat Cable



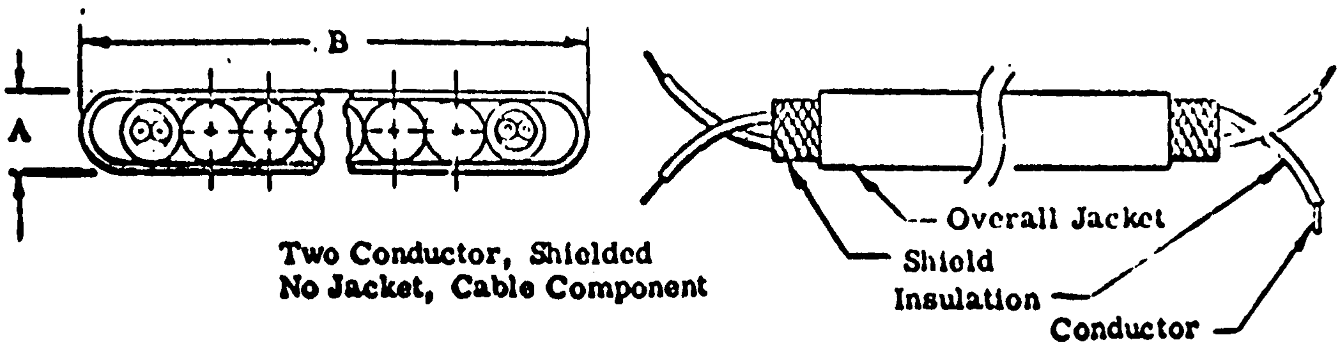
Multiple One Conductor Shielded Cable Component Flat Cable



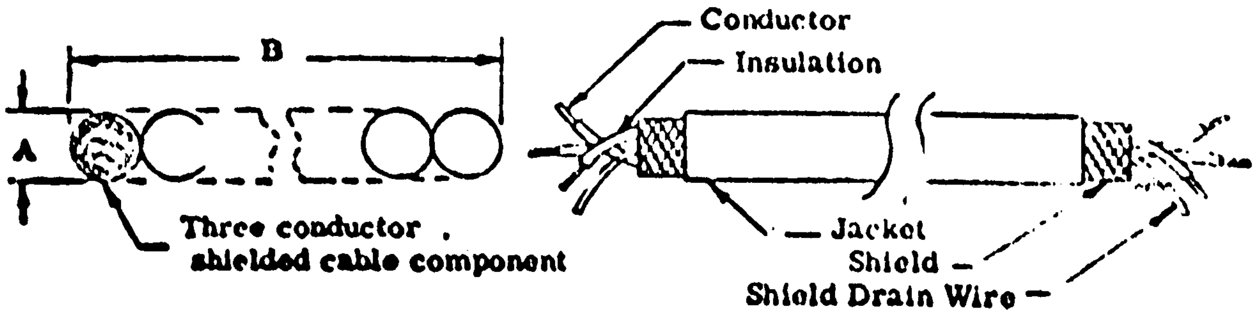
Multiple Two Conductor Shielded Cable Component Flat Cable



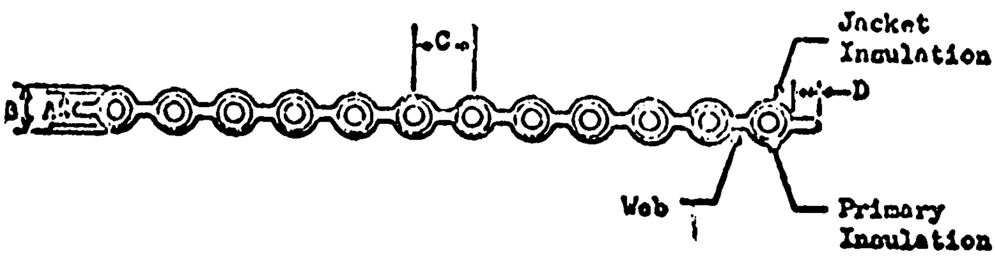
Multiple Two Conductor, Controlled Surge Impedance, Shielded and Jacketed Cable Component, Flat Cable



Multiple Three Conductor Shielded Cable Component Flat Cable



Using Jacket Insulation to Hold Insulated Conductors In Flat Cable Form



APPENDIX III

GLOSSARY

Connector. Mated plug and receptacle, designed to be separable and to connect a cable with another cable, printed circuit board, box, or component.

Corrosion. Destruction of the surface of a metal by oxidation or by some other chemical action. Can also be caused by reduction of the electrical efficiency between the metal and a contiguous substance or to the disintegrating effect of strong electrical currents or ground return currents in electrical systems. The latter is known as electrolytic corrosion.

Flat Conductor Cable. Cable consisting of flat parallel conductors held in place by either being laminated between thin flexible plastic insulating films or by some other equally effective method, such as extrusion or weaving.

Flex Life. The amount of time an insulating material can endure heat aging before it cannot be bent around a specific radius without failure. (Used to evaluate thermal endurance)

Flexual Strength. The strength of a material in bending.

Heat Endurance. The time of heat aging that a material can withstand before failing a specific physical test.

Housing. Outermost part of a plug, receptacle, or transition. Also known as a shell.

Plastic. High polymeric substances, used for insulation, including both natural and synthetic resin but excluding the rubbers, that are capable of flowing under heat and pressure at one time or another.

Plug. Part of a connector. Usually it is the part of a connector that, when connected, is the male component of the connector. Also, it is generally the movable portion of the connector.

Receptacle. Part of a connector. Usually it is the part of the connector that, when connected, is the female component of the connector. Also, it is generally the stationary portion of the connector and has provisions for mounting.

Ribbon Cable. Cable in a flat configuration and consisting of round wires or round cables.

Shielding. The confining of the dielectric field of a conducting cable to the insulation of the individual conductors with a conducting material, usually grounded.

Transition. A fixed connection from a flat conductor cable to round wire, printed circuit board, box, or electrical component, connection is permanent or disassembled only with difficulty.

Wire. Any conductor of round, square, or rectangular section, either bare or insulated.

MSFC CONNECTOR DEVELOPMENT

By Wilhelm Angele
MSFC-Research & Dev. Div.

A NEW NASA/MSFC CONNECTOR FOR FCC

Purpose

MSFC has developed a new series of NASA Flat Conductor Cable connectors, with individually sealed contacts. The series is designed to meet or exceed the FCC Specification MIL-C-55544 and will connect FCC to FCC, or to Round Wire Cables, or to Printed Wiring boards.

Figures 1 and 2 show a connector for FCC to RW connections.

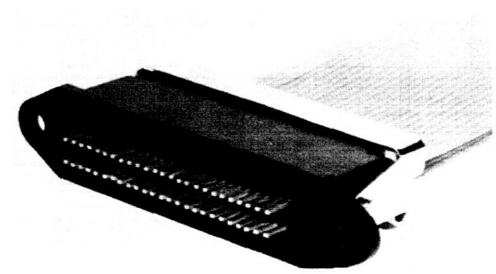


Figure 1. FCC to Round Wire Cable Connector with Individually Sealed Contacts, Mated View

The development of these connectors, with individually sealed contacts, is a result of many years of efforts to produce reliable FCC hardware capable of meeting aerospace systems requirements. The design of these connectors uses the conductors of the flat cable as contact surfaces.

A contract has been awarded to Astro-Space Laboratories, Inc. for the production of production tooling for two sizes of FCC to RWC connectors. It is hoped that this contractor will become a supply source, and that the problem of connector shortage will be greatly reduced or eliminated. This should also help to expand the application of flat conductor cable.

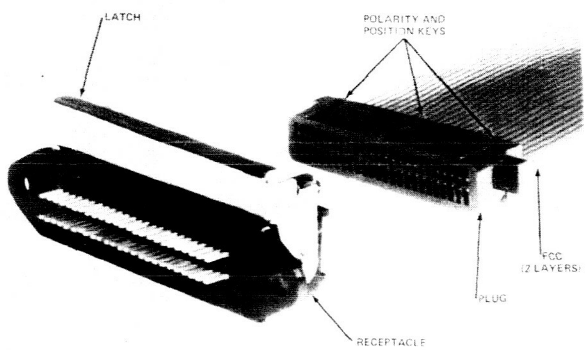


Figure 2. FCC to Round Wire Cable Connector with Individually Sealed Contacts, Unmated View

Design Approach

While the round wire connector industry, with few exceptions, applied the round wire connector design approach to FCC connector design, NASA/MSFC has been using an entirely different approach. Instead of adding pins and bushings to the wires, MSFC uses the cable conductor directly as contact surface. While some companies designed a termination for FCC which requires no stripping, MSFC's design uses stripped conductors. Stripping a cable is a very small effort when proper tooling is used. This latter approach results in a simpler connector with fewer parts.

Main Features of the New Design

Each contact of the connector has an individual seal against moisture and low air pressure, to avoid arcing or electrical leakage between neighboring contacts. This seal is accomplished by a strong over-center action safety-latch, which presses the face of the plug against a flat silicone rubber gasket. The safety-latch is a one piece double spring, easy to operate.

Another feature is the plug, molded of high temperature plastic, which provides a separate cavity for each contact. This plug is most inexpensive and lightweight, because it consists of only one relatively simple molded part.

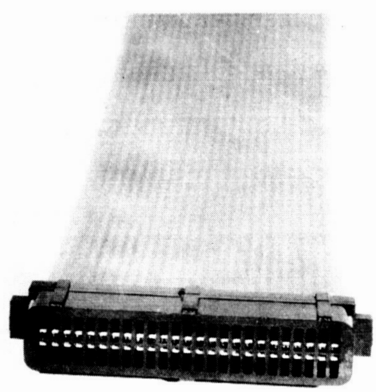


Figure 3. Multicavity Plug Terminated with Two Layers of FCC

General Connector Description

The connector consists of receptacle and plug. The receptacle consists of a die cast aluminum shell and a molded contact-spring retainer, which is fitted in the shell, then secured and sealed by potting compound. The shell also serves as hinge for the plug safety latch. The entire connector consists of only 7 parts, not counting the contacts: Plug, shell, insert, latch with two trunions and face seal. The design simplicity makes the connector inexpensive and contributes to its high reliability.

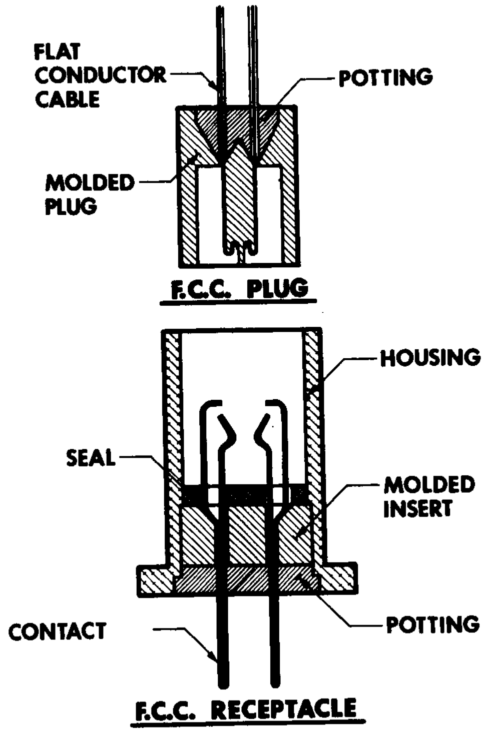


Figure 4. Cross Section of FCC to RW Connectors

Contact Spring Design Data

Much attention has been given to the contact spring design, amount of deflection, spring rate, contact force, contact form, etc. Notice the deflection of .025 inch (.6mm), which leaves ample room for manufacturing tolerances.

SPRING WIDTH AND THICKNESS	0.040 x 0.013 in.
DEFLECTION FOR MATING	0.025 in.
CONTACT FORCE	0.39 lbs.
SPRING RATE	15.6 lb/in.
HARDNESS, AFTER HEAT TREATMENT	Knoop 360-414
MODULUS OF ELASTICITY E	18.5×10^{-6} psi
MOMENT OF INERTIA I	0.77×10^{-8} in.^{4}
SECTION MODULUS I/c	$1/14 \times 10^{-6}$ in.^{3}
YIELD STRENGTH	$140 - 170 \times 10^3$ psi
STRESS AT MAX. DEFLECTION	102×10^3 psi
CONTACT FORM: SPHERIC, RADIUS	0.040 in.
SPRING PLATING: NICKEL	0.000 100 in.
GOLD, HARD	0.000 100 in.
FLAT CONDUCTOR WIDTH x THICKNESS	0.040 x 0.004 in.
HARDNESS	Knoop 74
MODULUS OF ELASTICITY E	16×10^6 psi
YIELD STRENGTH	10×10^3 psi
PLATING: SAME AS FOR CONTACT SPRING	

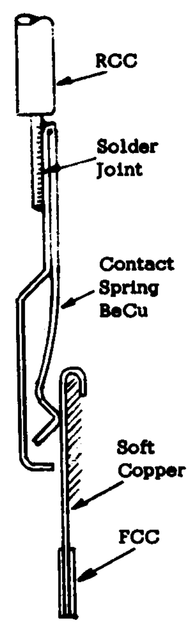


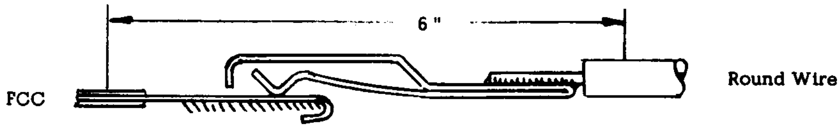
Figure 5. FCC to RW Contact with Typical Physical Data

Also of prime interest are contact quality and wear life. These two points are in competition and therefore require optimization. The contact has less than 1 mΩ resistance and lasts well over 500 insertions before the platings are worn through to the copper. At this point the connector still works properly. Substantial contact wear was observed after 1000 insertions, without failure. All tests were run without contact lubrication and without cleaning during the endurance testing.

Connector Electrical Data

Figure 6 gives some of the more important electrical information.
The electrical resistance measurement taken between 2 points, 6 inches apart, a measurement described in many specs, does not give an insight into the internal quality of the connector because the lead wires often have more resistance than the most vital electrical parts of the connector. For example, the chart shows the connector resistance with AWG 20 lead wire to be 7.9 mΩ but what really counts is the contact resistance itself, which is less than 1 mΩ and is very uniform. An increase of .5 mΩ for a contact indicates a defect. This increase of .5 mΩ cannot be easily detected in a total connector resistance when the lead wires are included. The specs need up-dating.

VOLTAGE RATING	300 V RMS
CURRENT RATING	3 AMP
INSULATION RESISTANCE	5000 Meg Ω



CONTACT CONSTRICTION RESISTANCE	0.5 mΩ
CONTACT SURFACE RESIST.	0.2 mΩ
CONTACT SPRING RESIST.	2.8 mΩ
INNER CONNECTOR TOTAL RESISTANCE	3.5 mΩ
TOTAL CONNECTOR RESISTANCE	
WITH AWG 27 LEADWIRE (22.4 mΩ)	25.9 mΩ
or AWG 20 LEADWIRE (4.4 mΩ)	7.9 mΩ

Figure 6. FCC to RW Contact with Typical Electrical Data

Connector Dimensions and Weight

Table I speaks for itself. A significant figure is the average connector weight per contact - just one gram.

Mounting the connectors in parallel fashion, on a 1-inch center will give ample clearance for operating the safety latch. If only two connectors are to be mounted, then the connectors can be much closer together and the latches hinged to the outside.

Table I. Physical and Mechanical Data for FCC to RW Connector

CONDUCTOR WIDTH .040"; CONNECTOR FOR 2 CABLES

CONDUCTOR SPACING .075"; CONNECTOR FLANCH .75" WIDE

FCC WIDTH	inch	1.0	1.5	2	2.5	3.0
NUMBER OF CONTACTS		24	36	50	64	76
CONNECTOR WIDTH	inch	2.2	2.65	3.18	3.70	4.15
RECEPTACLE WEIGHT	gr	25	32	42	51	59
PLUG WEIGHT	gr	4	6	8	10	12
CONNECTOR TOTAL	gr	29	38	50	61	71
WEIGHT PER CONTACT	gr	1.2	1.05	1.0	0.91	0.93
MATING FORCE	kg	0.9	1.4	1.8	2.3	2.7
UNMATING FORCE	kg	0.7	1.0	1.4	1.7	2.0

FCC Termination

The one piece molded plug, as can be seen in Figure 7, is the only part needed for cable termination. The FCC needs to be stripped, inserted into the plug, the conductors folded with a folding tool and the cable side of the plug potted for mechanical safety and protection against moisture.

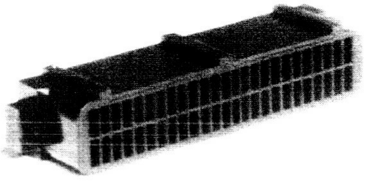


Figure 7. One Piece Molded Plug for FCC Individually Sealed Contact Connectors

Round Wire Connection

The connector described above is designed for interconnection of FCC to round wires. The wires can be soldered to solder lugs of the connector. Soldering can best be performed by using a soldering fixture. It provides bars with notches at 75 mils apart which hold the wires properly spaced and placed for gang soldering with optically concentrated heat. After the solder fixture is removed, insulation tubings can be slipped over the joint. Raychem Corporation has developed an even simpler system, in which the solder sleeves are heat shrinkable tubings.

Other NASA/MSFC Connector Types

As mentioned before, we also have developed a connector for connecting FCC to FCC. Figure 8 shows a sample for 2-inch wide cables.

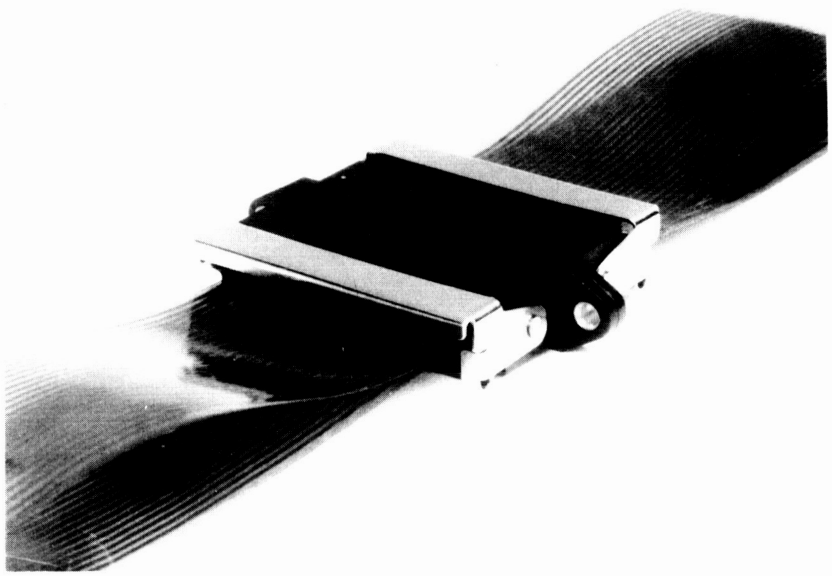


Figure 8. FCC to FCC Connector with Individually Sealed Contacts

The contact spring design for the FCC - FCC Connector is similar to the FCC - RWC Connector. The mechanical and electrical data shown below are also similar.

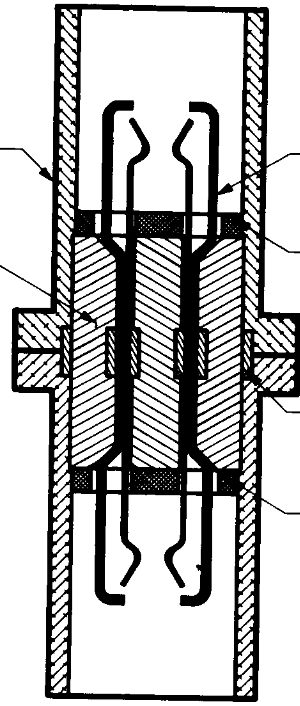
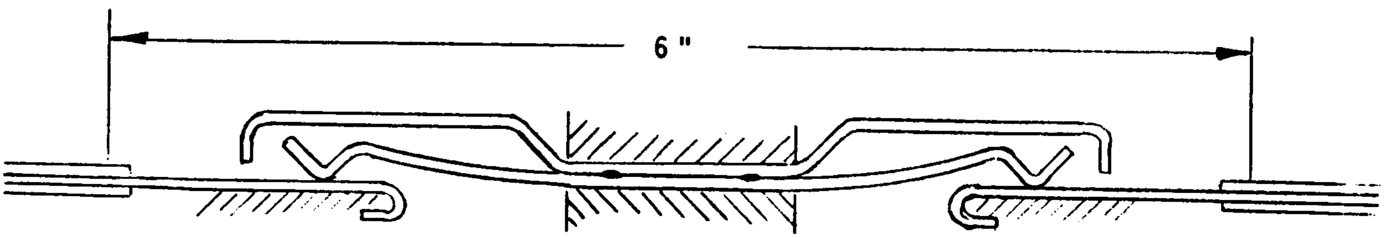


Figure 9. Cross Section of FCC to FCC Connector



CONSTRICTION	(2 places)	1.0 mΩ
SURFACE	(2 places)	0.4 mΩ
CONTACT SPRING		4.4 mΩ
INNER CONNECTOR		5.8 mΩ
AWG # 27 LEADWIRE		21.4 mΩ
TOTAL CONNECTOR	(6 inches)	27.2 mΩ
or		
AWG # 20 LEADWIRE		4.2 mΩ
TOTAL CONNECTOR	(6 inches)	10.0 mΩ

Figure 10. FCC to FCC Connector Contact with Typical Resistance Data

Table II. Physical and Mechanical Data for FCC to FCC Connectors

CABLE WIDTH	in.	1.0	1.5	2.0	2.5	3.0
RECEPTACLE WEIGHT	g.	50	60	70	80	90
WEIGHT OF TWO PLUGS	g.	8	12	16	20	24
CONNECTOR TOTAL WEIGHT	g.	58	72	86	100	114
WEIGHT PER CONTACT	g.	2.4	2.0	1.7	1.6	1.5
MATING FORCE, MAXIMUM	Kg	.9	1.4	1.8	2.3	2.7
UNMATING FORCE, MAXIMUM	Kg	0.7	1	1.4	1.7	2

Another version is the FCC to Printed Wiring Board Connector. The safety latch is replaced by other means to keep the PC board firmly inserted in the receptacle. Also, provisions are made for various standard thicknesses of PC boards.

Keying System for Plug and Receptacle

The keys serve 3 functions:

1. To give guidance for the plug and to avoid binding or cocking during insertion.
2. To assure proper polarity between plug and receptacle.
3. To act as position key, to make sure that the right plug goes to the right receptacle.

To accomplish the first point there is a set of center keys, tongue and groove, with close tolerances.

Two additional sets of keys are provided for proper positioning of the plug with respect to the receptacle, thereby preventing wrong connections. This positioning key can have various distances from the center key, thus providing a large number of possibilities for avoiding miss-matches.

Both key systems also function as polarity keys.

This concludes the description of the new connector series. A report about this connector (NASA TMX-64695) in much more detail is being published. We hope the connector will help alleviate the problem of inadequate connecting hardware supply, and by so doing, make a significant contribution toward the widespread application of FCC.

DESCRIPTION OF CRIMP CONTACT

By Jon Wigby
Burndy Corp.

TAPECON MARK II - "NO-STRIP-CRIMP CONTACT

INTRODUCTION

Flat electrical signal cables have become a necessity! Communications, computers, business machines, shipboard, airborne, and aerospace applications are demanding flat cables. Why are they necessary? They are efficient and labor saving. Where are the reliable connectors for these cables?

We manufacture three different types of connections for this market. This paper is about one of these; the Tapecon Mark II - "no-strip-crimp connection. The following features are fundamental to this design:

1. Contact mates with copper conductors spaced on 50 mil centers or larger.
2. Insulation removal or stripping is unnecessary.
3. Cable thicknesses up to .030 in. can be accommodated.
4. Contact provides a gas tight joint.
5. Contact provides oxide removal during crimp.
6. It maintains residual contact pressure.
7. Contact accommodates tap or terminations.
8. Many contacts can be installed simultaneously on the cable.

CONTACT DESCRIPTION

These features are encompassed in the design shown on Figure 1. The contact material is copper alloy formed with progressive dies. (Figure 2) One end is coined to provide spring properties. This spring provides a disconnectable joint with .025 round or wire wrap pins. These spring properties have been developed and proven for similar applications. The other end of this contact has properties conducive to crimping. The

crimp end consists of two legs with opposing rows of teeth. The teeth and jaw opening are adaptable to different cable thicknesses up to .030 inch thick. The legs and teeth are brought into contact with the cable via two opposing confining die sets. Optimum crimp dimensions have been established for different cable thicknesses. The teeth are offset to provide a meshing action as the crimp is initiated. Proper alignment between teeth is ensured by the relief slots at the outer periphery of the legs. The slots allow the legs to deform slightly during tooth meshing to provide continuous alignment, uniform pressure between teeth, and proper skiving of insulation.

At the completion of the crimp the two high points on each relief slot have closed up, forming a tear drop shaped opening. The outer surface thus confined in the crimp die is loaded in compression and the teeth are loaded in tension. In other words, the cable conductor and tooth have filled the valley between the two opposing teeth causing these teeth to spread apart slightly (they are tensile loaded). The combined compressive load on the outer contact edge and the tensile loading at the roots of each tooth provide a load couple which ensures continued or residual contact loading onto the cable. The contact can be either tin or gold plated. Tin platings work the best. The ductility of tin promotes excellent conductivity and environmental protection.

A blow up of a tin plated tooth section (Figure 3) shows how the conductor thickness is reduced, the tin plating is plowed up and a metallic interface is formed between tooth, tin plating and conductor.

CONTACT ASSEMBLED

Several contacts can be installed on the cable at one time. Figure 4

shows tin plated contacts installed on a vinyl/polyester insulated cable with .100 inch center spacings. Tests were also conducted on .050 inch center-to-center spaced conductors using mylar, FEP, and vinyl insulations with good results. Six hundred samples were tested in groups of ten each. A nylon magazine rod was used to provide a carry strip for gang crimping. Other types of magazines can be used. These cable assemblies were further assembled into a cut-to-fit connector body type shown on Figure 5. This plug and receptacle assembly was then environmentally tested to a modified MIL-C-55544 test specification.

The following test results are specifically for tin plated contacts installed on .100 inch center-to-center spaced conductors with mylar insulation. The data is presented as bar charts using upper and lower 3σ to predict the sample data spread. Bulk cable resistance values were measured over 1.7 inches of cable length. These values are shown as horizontal lines on the following charts. This data provides a direct comparison with the crimped test samples also measured over 1.7 inches.

CORROSION TEST

The corrosion test was performed (per MIL-STD-202D, Method 101C, Condition B) with 5% salt spray. The connectors were previously conditioned by vibration and shock. Two termination groups and one tap group are shown on Figure 6. All connectors passed with less than 8 milliohm average resistance measurement. The largest sample distribution is evident for the terminations of ±4.5 milliohms and ±2 milliohms for the tap. The tap sample maintained a lower average conductivity with a smaller 3σ spread.

Bulk cable compared to crimped resistance readings are very similar. The cable itself has a ±0.70 milliohm 3σ spread. In nearly all instances, the resistance values after exposure are higher than initial readings. Only one group of terminations had lower resistance values and a smaller statistical spread initially. This situation is possible with contacts crimped thru the insulation, and occurs when the cable has variations in plastic insulating qualities sufficient to trap plastic in the joint. Under the effect of residual loading, given time or temperature the plastic becomes forced out of the joint thereby establishing an improved electrical connection. The corrosion test samples performed very well with vibration and shock treatments (per MIL-STD-202D, Method 204, Condition D and Method 213 and Condition A, respectively) performed prior to corrosion exposure. The testing was concluded with 500 cycle durability test and resistance measurements. The samples were found electrically sound.

HUMIDITY TEST

The humidity exposure was conducted per IBM 4-4-16 test sequence after a high temperature exposure for 1000 hours (per MIL-STD-202D, Method 108, Condition D). There were no sample failures and samples averaged 7 milliohms with ±3.75 milliohm 3σ spread, as shown on Figure 7. This test is severe and the moisture molecules tend to penetrate any holes or crevices. The cable conductors became oxidized at the trimmed ends and moisture penetrated up the cable past the crimp without damage to the joints.

THERMAL SHOCK

The thermal shock test was conducted (per MIL-STD-202D, Method 107C, Condition B) on a separate group of samples with resistance measurements taken before and after cycling. The bar charts shown on Figure 7 represent contacts crimped to flat conductor flat cable without insulation

stripping. The average resistance readings initially were less than 7 milliohms and did not exceed ±1.5 milliohm spread. These were properly crimped samples and the final readings increased the same amount after thermal shock testing. The crimped resistance reading after exposure exceeded the cable average by only 1 ohm. These results are very good.

LIFE TEST

The 1000 hour life test group was exposed (per MIL-STD-202D, Method 108, Condition D) at 80°C for 1000 hours. This test provides some criteria as to aging and gives an indication how well the contact retains its residual load characteristics. Figure 8 shows that the average values remained below 7 milliohms after exposure with ±1.25 maximum 3σ spread. The average crimp values are practically identical with the bulk cable measurements, and underscore the long term capabilities of this contact.

Additional tests showed that dielectric strength of these contacts assembled in the connector bodies exceeded 1500 VAC. Cable retention exceeded 25 pounds per inch, and insulation resistance met MIL-STD-202D, Method 302, Condition B.

IN CONCLUSION

The Tapecon Mark II crimp contact meets the fundamental features mentioned earlier.

1. We tested the contact on .050 and .100 inch cable spacings - .100 spacing was discussed above but is capable of .050 inch spaced conductor usage.
2. We tested tap configurations on mylar cable doubled to .022 - .026 thickness - .030 inch thicknesses are possible.

3. The contact remained electrically sound and gas tight under salt spray, humidity, and high temperature exposures.

4. The contact removes both oxides and insulation to achieve low initial conductivities.

5. The contact maintained contact pressures (residual loading) with a variety of exposures but especially under 1000 hour high temperature exposure.

6. Tap connections and terminations are both feasible as shown under many exposure conditions.

7. Simultaneous contact installation is the method by which all the test groups were made. The upper and lower 3σ data provides a meaningful method of evaluating many crimp joints.

The versatility of this connector principle for flat signal cable is immense and should grow along with the new demand for flat signal cable.

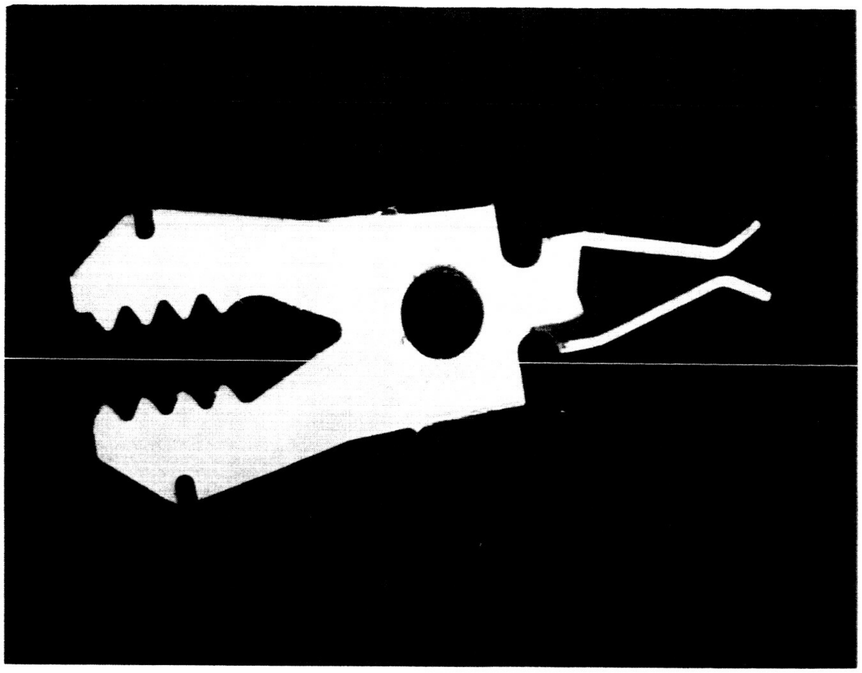


FIGURE 1

NO-STRIP-CRIMP CONTACT CLOSEUP

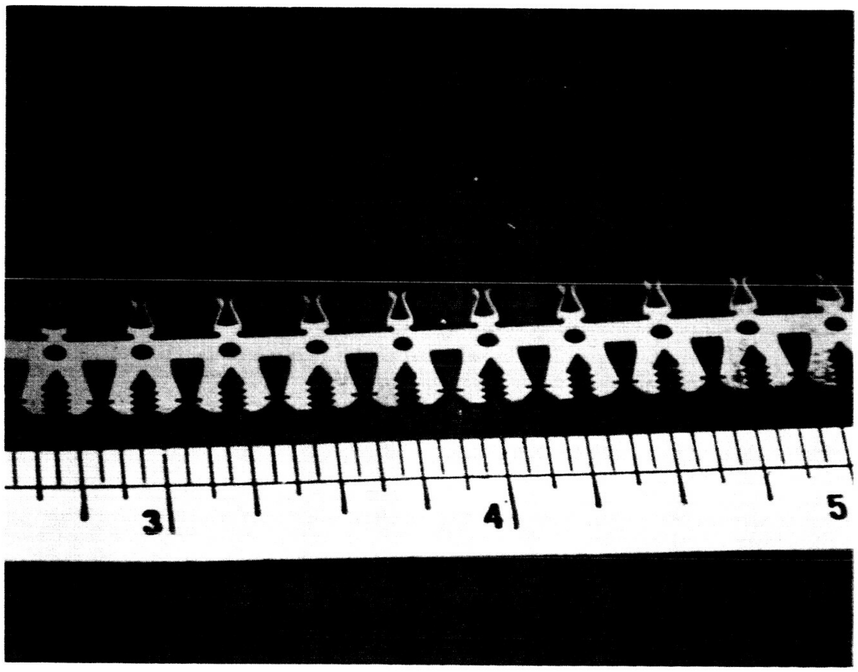


FIGURE 2

CONTACT AS PRODUCED

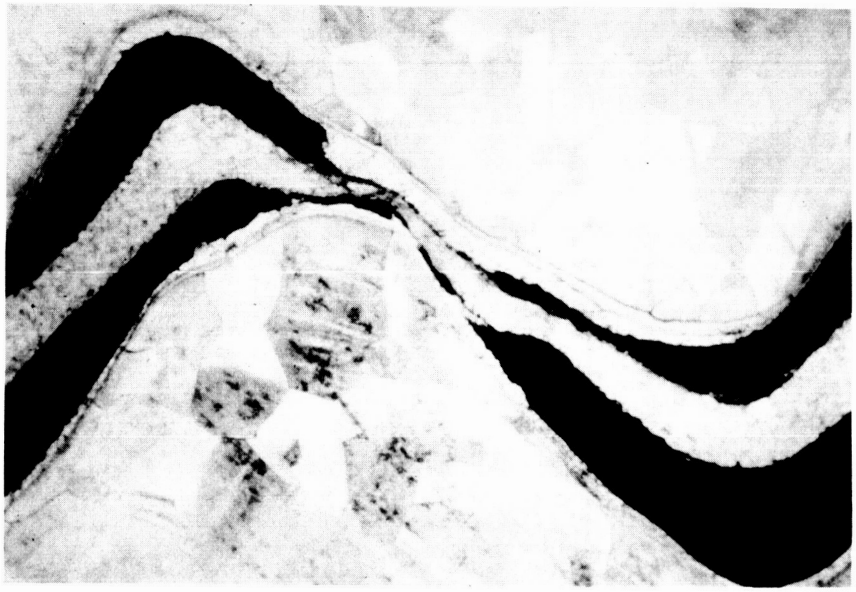


FIGURE 3

100X PHOTOMICROGRAPH OF TOOTH CONTACT JOINT

FIGURE 4

CONTACT CRIMPED TO CABLE

FIGURE 5
CONTACT ASSEMBLED IN CUT-TO-FIT
CONNECTOR WITH MATING PLUG & HARDWARE

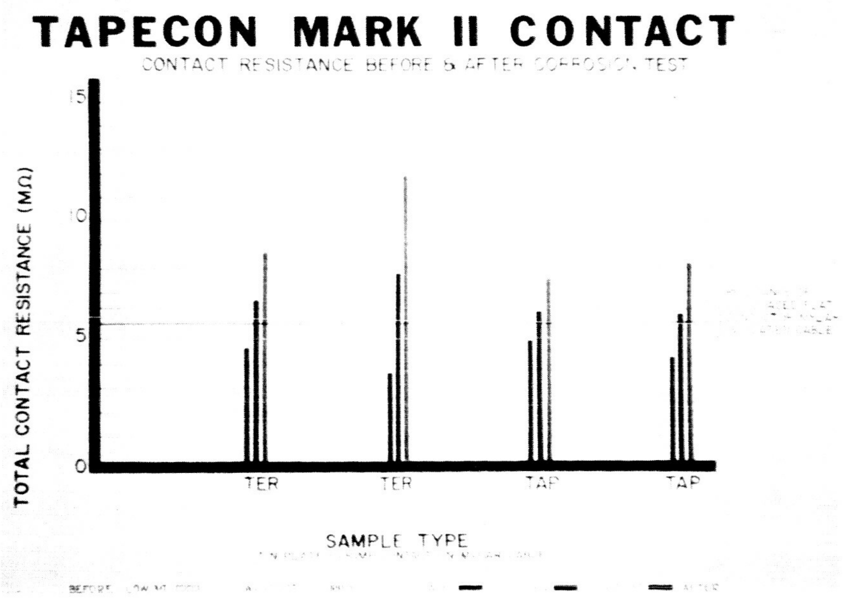


FIGURE 6

CONTACT RESISTANCE VS. CORROSION TEST

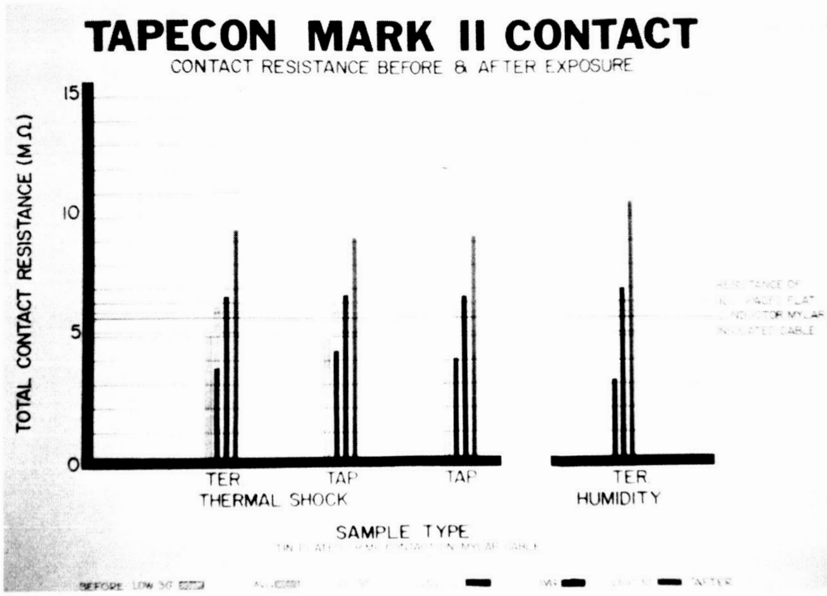


FIGURE 7

CONTACT RESISTANCE VS.
THERMAL SHOCK & HUMIDITY

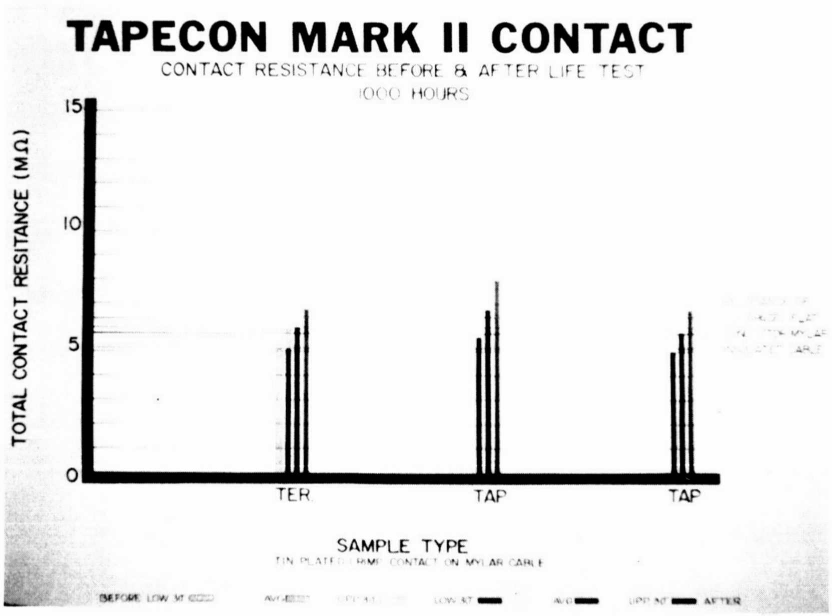


FIGURE 8

CONTACT RESISTANCE VS.
1000 HOUR LIFE TEST

CONNECTOR INTERCHANGEABILITY

By Thomas Berilla
Department of Defense

CONNECTOR INTERCHANGEABILITY

ANSI* Y14.5 RULES

Abstract

Mr. Berilla's presentation will:

1. Present the purposes for using the General Rules of ANSI Y14.5.

2. Define the Rules with examples using Maximum Material Condition, Least Material Condition, True Position, and Regardless of Feature Size.

3. Apply the Rules step-by-step to a mechanical assembly.

4. Show why the ANSI Y14.5 format is beneficial to functional design, interchangeable fit, and lowering costs.

5. Compare clearance hole and fixed feature (threads, dowels, etc.) applications to Zero Positional Tolerancing and Assigned Positional Tolerancing methods.

6. Apply the General Rules to actual connector designs.

7. Coordinate in design:

   a. Functional End Product Specifications.

   b. Economical Processing.

   c. Inspection Methods to Assure Quality.

8. Demonstrate how analytical worst-case tolerance analysis and paper gaging are applied to products designed with the General Rules.

9. Identify existing specifications that:

   a. Can reject better quality products than those they accept.

   b. Can accept products which should be rejected.

   c. Impose unnecessary, non-functional and costly requirements.

10. Conclude by demonstrating with actual products how the General Rules of Y14.5 optimise costs, quality, producibility, performance, and interchangeable assembly.

* American National Standards Institute

WHY

M L ⊕ S ?

If the electrical connector industry would adopt the GENERAL RULES of the American National Standards Institute Y14.5 Drafting Standard for Dimensioning and Tolerancing on its engineering drawings, electrical connectors would be specified in a manner that would optimize their costs, mechanical performance, interchangeability, inspection and quality requirements, and ability to be manufactured. The DoD calls all this MIL-D-1000, Category E and F in accordance with MIL-STD-100 requirements. However, these General Rules which define Maximum Material Condition, True Position, and Regardless of Feature Size have been found difficult to accept by Users because the rules and benefits are not well understood.

ANSI Y14.5 is really a book of many drafting standards rather than one simple standard. From the pages of Y14.5 any designer could find that any common or customary dimensioning and tolerancing practice is allowed by these standards and yet never find how designs could be optimized for performance and economy by using the best one for all electrical connector designs, or for that matter any mechanical design. There are three basic principles within Y14.5 that are tools which best serve specific design purposes and each has its own appropriate application. These are Maximum Material Condition, M , True Position, ⊕ , and Regardless of Feature Size, S .

M defines the limits of perfect form, perfict fit, and the tightest fit that can exist in an assembly. Of course, it should be understood that the Least Material Condition, L , would be the least acceptable or the loosest fit that would be allowed in an assembly. Therefore:

1. The limits of M and L would be a zone defined by the limits of size for a feature and be the limits between which all parts produced must fit to be acceptable. See Figure 1.

2. ⊕ defines dimensions of position as established from the perfect form of the product.

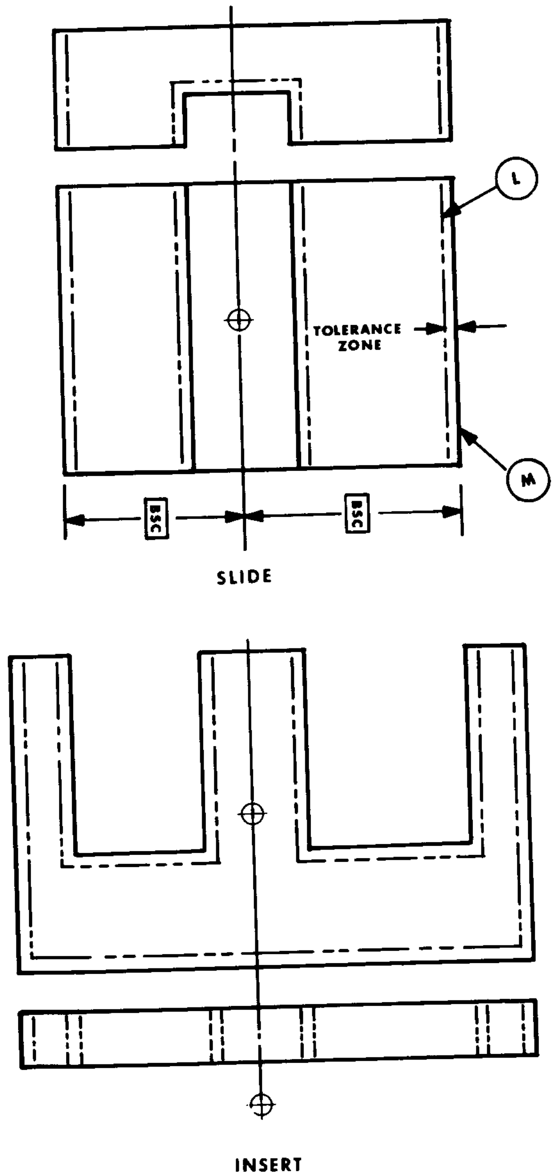
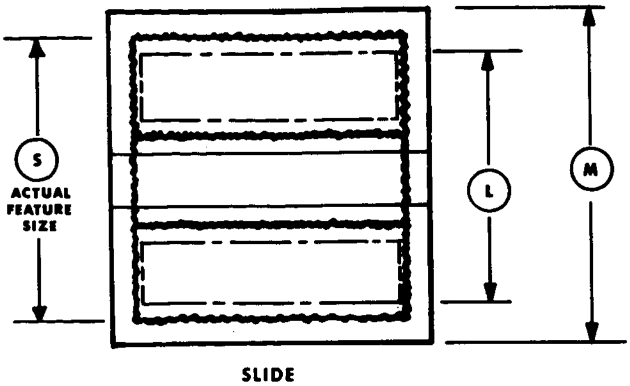


FIGURE 1

3. (S) is the actual condition that exists on any actual feature of any particular part. See Figure 2.

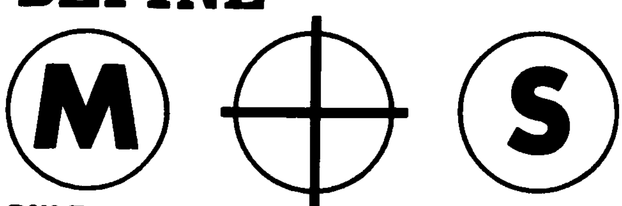


(S) CONTROLS FORM TOLERANCES.
(NOT USED FOR LOCATING.)

FIGURE 2

The General Rules of Y14.5 that apply to (M), ⌖, and (S) are found on pages 34, 35, and 36 of the 1966 edition of Y14.5. You may read these three pages of the General Rules and the subsequent hundred or so pages that try to explain their application. However, let us paraphrase the Rules to simplify them for your use and extend their principles into electrical connector designs.

THREE GENERAL RULES DEFINE



RULE 1

(ALL STATIC AND MOST DYNAMIC DESIGNS.)

DIMENSIONS OF SIZE SHALL BE SPECIFIED AS LIMITS BETWEEN (M) and (L). THESE LIMITS CONTROL A FEATURES FORM AS WELL AS ITS SIZE.

RULE 2

(ALL STATIC AND MOST DYNAMIC DESIGNS.)

DIMENSIONS OF POSITION AND RELATED DATUMS ARE ESTABLISHED FROM (M) (DEFINES ⌖)

(SEE FIGURE 3)

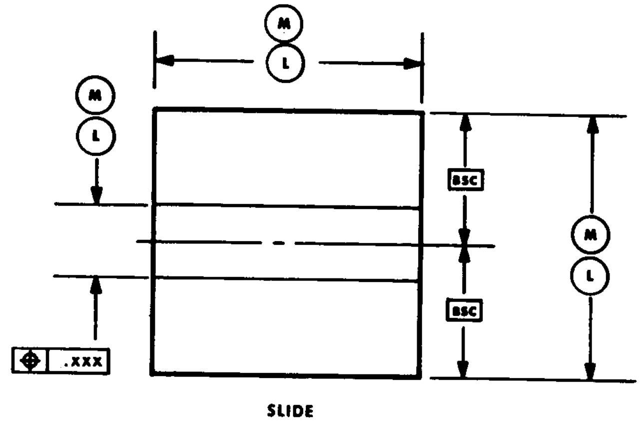


FIGURE 3

RULE 3

(DYNAMIC DESIGNS: WHEN NECESSARY)

FORM TOLERANCES AND THEIR RELATED DATUMS ARE ESTABLISHED FROM THEIR RELATED FEATURE (S)

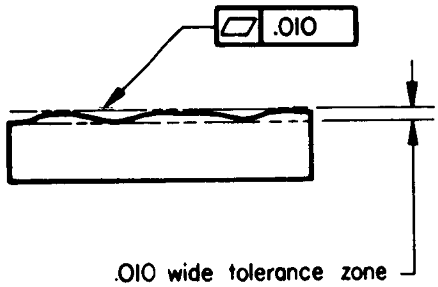
⏥ FLATNESS	∥ PARALLELISM
— STRAIGHTNESS	∠ ANGULARITY
○ ROUNDNESS	⊥ PERPENDICULARITY
⌭ CYLINDRICITY	↗ RUNOUT
⌒ LINE PROFILE	◎ CONCENTRICITY
⌓ SURFACE PROFILE	⌯ SYMMETRY

FORM TOLERANCE SYMBOLS

FIGURE 4

Note that Rules 1 and 2 apply to all static designs, i.e., the product must meet assembly and interchangeability requirements regardless of any dynamic requirements. Therefore, the only tools the designer requires for interchangeable requirements are (M), (L), and ⌖ as are defined by Rules 1 and 2. Only when dynamic requirements actually influence a feature must the form tolerances of flatness, perpendicularity, symmetry, concentricity, etc. be superimposed between the limits of (M) or (L). It must be emphasized that to justify the additional use of any of the form tolerances in a design, there must be a requirement for some dynamic outside force that is imposing its influence on a feature that cannot be controlled within the limits of (M) and (L). In other words, an action verb must always apply when a form tolerance is specified. Examples of dynamic action are:

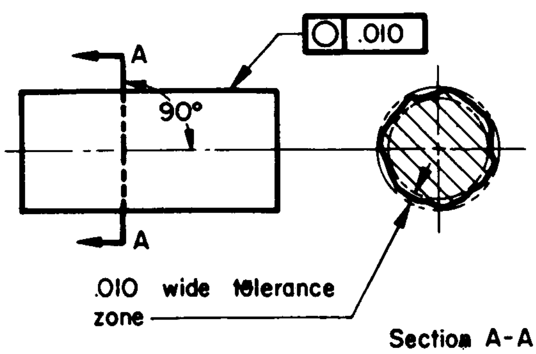
When a surface is not flat, Figure 5, it will <u>not seal leaks</u>, <u>reflect light</u>, <u>prevent wobble</u>, etc.



The surface must be within the specified tolerance of size and must lie between two parallel planes (.010 apart). (S)

FIGURE 5

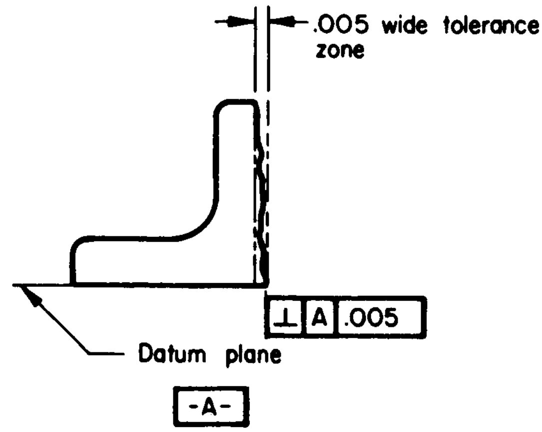
When a shaft is not round, Figure 6, it will <u>wobble</u>, <u>not seal leaks</u>, <u>vibrate when it rotates</u>, <u>chatter in a bearing</u>, <u>cause excessive wear</u>, etc.



The periphery at any cross section perpendicular to the axis must be within the specified tolerance of size and must lie between two concentric circles (one having a radius .010 larger tha the other). (S)

FIGURE 6

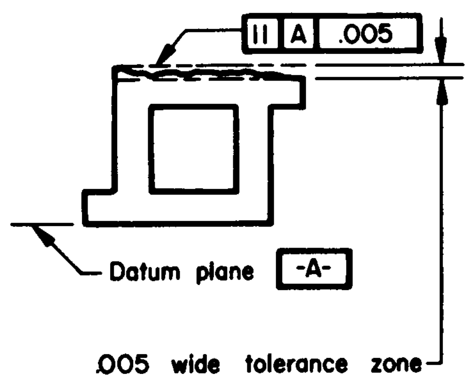
If a feature is not perpendicular, Figure 7, it will <u>look crooked</u>, <u>not reflect</u>, <u>not seal</u>, etc.



The surface must be within the specified tolerance of size and must lie between two parallel planes (.005 apart) which are perpendicular to the datum plane. (S)

FIGURE 7

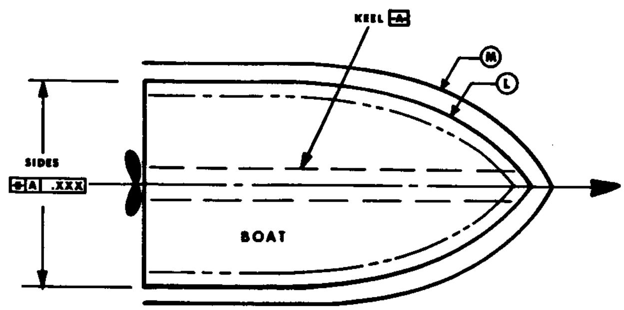
Parallelism, Figure 8, <u>controls sealing</u>, <u>appearance</u>, <u>wobble</u>, etc.



The surface must lie between two planes (.005 apart) which are parallel to the datum plane. (S)

FIGURE 8

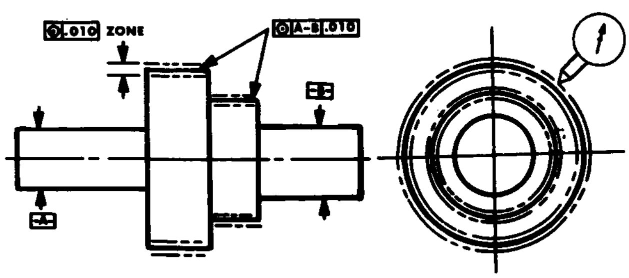
Symmetry, Figure 9, <u>controls appearance</u>, <u>balance</u>, <u>the flow of fluids over a surface</u>, (i.e. a keel must be symmetrical to the sides of a boat regardless of the boat's size), etc.



SIDES MUST BE SYMETRICAL Ⓒ TO KEEL WHEN MOVING THRU WATER.

FIGURE 9

Concentricity, Figure 10, <u>controls balance</u> such as when a shaft has eccentric features along its axis of various diameters that would <u>cause vibration</u> when a shaft rotates at high speed.



ALL FEATURES MUST BE CONCENTRIC WHEN SHAFT ROTATATES AT HIGH SPEED. Ⓢ

FIGURE 10

The form tolerances are superimposed, restrictive, added expense that must be justified very seiously before use. Many connector designs have imposed upon them unnecessary form tolerances that contribute nothing to quality, lower cost, performance, reliability, or interchangeability for a connector assembly. Form tolerances are no doubt the most misapplied and abused practice in electrical connector design. Since form tolerances are established Ⓢ , inspection must be by dial indicator or a similar expensive device; instead of a simple GO and NO-GO gage.

<u>Applying the Rules</u>

To understand correct application of Ⓜ , Ⓛ , ⌖ , and Ⓢ , let us take the simplest mechanical design that can apply the General Rules and show how they are used in <u>all</u> mechanical dimensioning and tolerancing situations. Afterwards, we will apply them to some connector designs.

Figure 11 shows a 4 x 2 inch hole, two plates which are 4 x 2 inches in size and two half-inch bolts with nuts that will assembly the plates. When the plates are assembled, they are required to always fit in the 4 x 2 inch hole and with complete interchangeability.

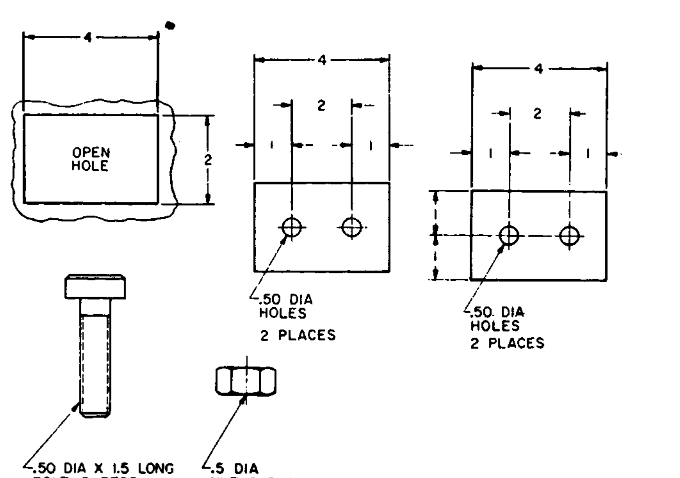


FIGURE 11

Figure 12 shows the assembly of two plates with the bolts. The configuration of the 4 x 2 hole and the plate assembly is that which defines perfect form. In other words, you would have a line-to-line fit between the hole and the assembled plates if all these features were made to perfect form of the 4 x 2 inch dimensions. This defines the Ⓜ, a condition of perfect form and fit, of an assembled system. Many people would argue that this system as defined is not possible to achieve because it is a perfect configuration; and nothing is perfect. This is true, but please accept that this is perfection defined, but not achieved. However, perfection should be the goal of every design.

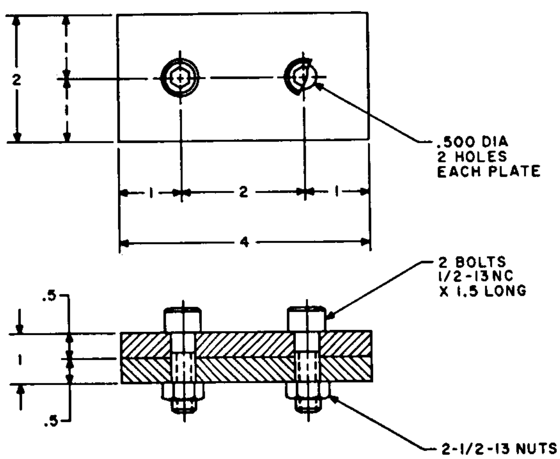


FIGURE 12

Since perfection can never be achieved, designers must specify tolerances which are limits, allowable errors, deviations, or variations that processors must have to make a product so that it is economical to process and to be affordable to customers. If we can accept the idea that tolerance is a derivative of the word "tolerate", then we can accept the idea that the only thing that we can tolerate is error. Therefore, error or tolerance is the degree of variation or deviation that is allowed from perfection so that we can afford our products. The only direction that we can go from perfection is away from it; and for most purposes the direction is one which must provide clearance. The more a feature varies from perfection, the lower will be the product quality; but the more a feature can be allowed to deviate without seriously affecting performance, the lower should be the product's cost. Therefore, the assembly of Figure 12 should have tolerances applied that will not produce interference, excessive clearance, or imbalance that would affect its interchangeability at assembly or its performance.

Please accept that the only performance requirements of this assembled system is that the product must fit interchangeably because there will be an infinite number of assemblies made. If this is so, then imbalance can be ignored for this particular requirement. Ⓢ and its associated form tolerances will not be specified because Ⓜ and Ⓛ will control form with Rule 1.

Let us now apply General Rule 1 to our design. Note that in Figure 12 the basic dimensions of design are given without tolerance. This Ⓜ and ⌖, a condition of perfect fit between plate, bolt and the open hole when the assembly is completed. From this Ⓜ, the only deviation permissible would be to increase the size of the 4 x 2 inch hole or to allow the 4 x 2 inch plate to decrease in size. The ½ x 13 bolts are at Ⓜ at their ½-inch diameter.

The plates are then defined as seen in Figure 13. Note that we have defined limits of size for the ½-inch holes as being .500 diameter to .502 diameter in accordance with Rule 1 for Ⓜ and Ⓛ. The dimensions of ⌖ have been identified by placing them in boxes. Note that the sum of chained basic dimensions of position (i.e., 1 + 2 + 1), add up to the 4 inch Ⓜ for the plate length. This fulfills the rule that says that dimensions of position are established from Ⓜ. Notice that there are two feature control symbols

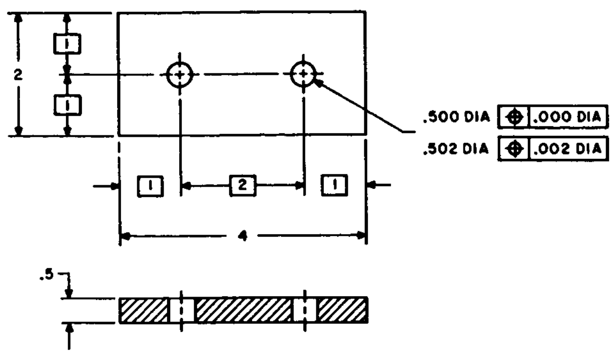


FIGURE 13

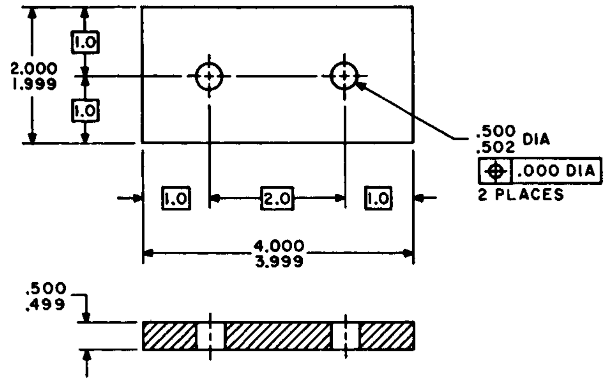


FIGURE 14

associated with the hole sizes. The first feature control symbol says that if a hole is made to .500 diameter, then it must be located within a ⌖ zone of .000 diameter; (perfectly located). If the hole is made to .502 diameter, then it may be located within a radius of .001 inch from ⌖ or within ⌖ of .002 inches diameter. What this means is that tolerances of position are dependent upon feature size. When the feature, i.e., the ½-inch hole, is made to Ⓜ, then the bolt hole must be located perfectly. If a feature such as the bolt hole is made larger, then the additional clearance provided by the larger hole permits a greater deviation or tolerance from ⌖; therefore, the hole can be located off center to the proportionate limits and still permit interchangeability. This system of dimensioning and tolerancing is called ZERO POSITIONAL TOLERANCING; which allows that the range of hole sizes and positional tolerances be expressed as shown in Figure 14.

Figure 14 shows the ½-inch hole expressed as .500 Ⓜ and .502 Ⓛ as dimensions and limits of size. In addition, the feature control symbol shows that each hole must be within ⌖ of .000 diameter and this feature control symbol implies that the tolerance applies at Ⓜ of the holes. In addition, it also implies that as the feature departs from Ⓜ in the direction of Ⓛ, the proportionate tolerances of position is allowed in the exact amount that the hole size departs from Ⓜ. In other words, as the hole gets bigger so do the allowable positional tolerances for the feature get bigger. Note that the dimensions of position are still identified as being basic without tolerance and are placed in boxes. It must be stressed at this time that the dimensions of position never have a tolerance. Positional tolerances always apply to the feature, and features vary from ⌖. In addition you should recognize that the shape of any tolerance zone will always be determined by the shape of the part.

Figure 14 also shows that size tolerances have been applied to the length and width of the plates. The width can vary from 2" Ⓜ and 1.999 Ⓛ. In like manner the length is 4.000 Ⓜ and 3.999 Ⓛ. Again, it is

stressed that the sum of the chained dimension of position that are given as basic must add up to Ⓜ ; and that the Ⓛ dimensions of 1.999 or 3.999 have no relationship to the dimensions of position since dimensions of position apply only to Ⓜ . Figure 14 completely describes all plates to fit with interchangeability; <u>however</u>, the tolerances assigned are <u>very expensive</u>.

<u>Optimizing Cost and Fit</u>

Figure 15 now shows the options the designers have to reduce product cost, achieve interchangeability, and determine the quality for performance that is functionally required for the application. Basically, this means that the Ⓛ limits can be varied to reduce costs because Ⓛ departs from Ⓜ in a direction that always allows clearance in an assembly. In other words, Ⓜ is <u>not negotiable</u>, but Ⓛ <u>is negotiable</u>. The greater the range between Ⓜ and Ⓛ , the lower will be the product cost and quality as Ⓛ approaches a limit that is so sloppy, the assembly will not properly work. Ⓛ is determined by testing, the designer's judgment, manufacturing costs for various operations, and mostly by what the performance of the product requires.

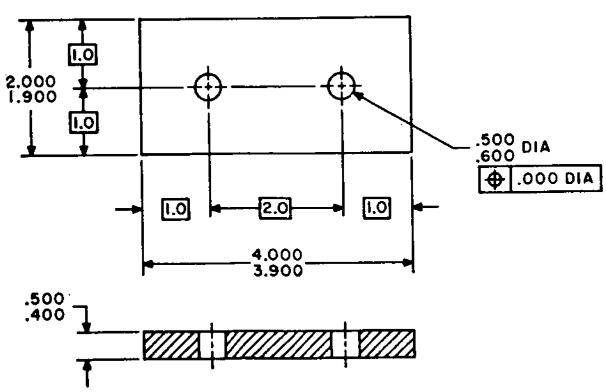


FIGURE 15

Figure 15 shows how to optimize tolerances to reduce cost and still allow the product to perform within acceptable quality limits. Note that the range between Ⓜ and Ⓛ of the length and width has increased to .100 inches to allow a considerable variation Additional savings and adequate performa are not expected if the tolerances were broader. This means that if the plates were assembled and made to Ⓛ , they would work satisfactorily in a 4 x 2 inc hole. We do not know at this time what the Ⓛ of the hole will be, but for the sake of this problem, let us conside that the 4 x 2 inch hole will always be perfect. In addition, the clearance hol for the ½-inch bolt vary from .500 to .600 inches diameter. If a clearance hole is made to .500 inches, then the hole locations must be held perfectly. If either hole were made to .600 inches diameter, then either hole could vary from .000 up to .050" in radius or withi a zone about true position which is .100" diameter. Figure 16 tabulates this ZERO POSITIONAL TOLERANCING method. <u>No</u> method of specifying dimensioning and tolerancing is more economical or ideal than zero positional tolerancing.

ZERO P.T. CHART	
HOLE DIA	P.T. FROM
.500 Ⓜ	.000 DIA
.501	.001 DIA
.502	.002 DIA
↕	↕
.599	.099 DIA
.600 Ⓛ	.100 DIA

AXIOM:
P.T. ALWAYS DEPENDS ON FEATURE SIZE.

FIGURE 16

Benefits of Ⓜ , Ⓛ and ⌖

Figure 17 is a completed plate design that graphically shows what Figure 15 would look like if the limits of size and the positional tolerance zones were graphically portrayed. Ⓜ is shown as solid lines and Ⓛ is shown as phantom lines.

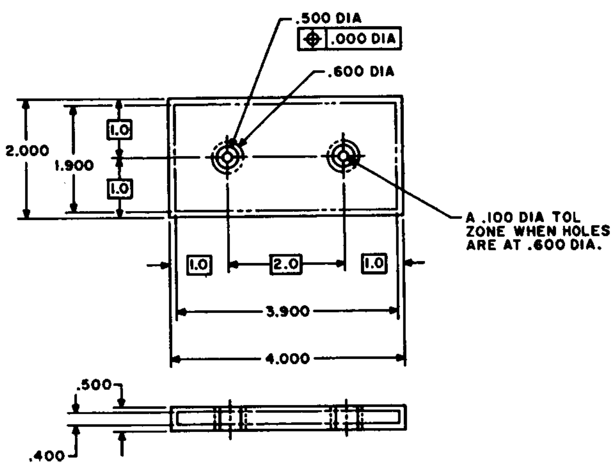


FIGURE 17

The solid lines represent:

A. Perfect form at perfect fit.
B. Maximum Material Condition.
C. The GO Gage.
D. The basic original layout of the product from which all deviations apply.
E. Perfection defined.
F. Dimensions of Fixtures and tools used for locating parts in manufacturing.
G. The pattern from which ⌖ is located.

The phantom lines represent:

A. Perfect form at the least or worst acceptable fit.
B. Least Material Condition.
C. The NO GO gage.
D. The worst acceptable form that can be made from any manufacturing process and yet functions in an assembly.
E. The condition beyond which the product can no longer depart from Ⓜ and still be acceptable and work at the required performance. (This is similar to a nearly wor-out part that has excessive clearances.)
F. The loosest fit or the easiest part to assembly.

This completes the design for the simplest application for defining and applying the General Rules 1 and 2 of ANSI Y14.5. The unique benefits of describing designs in accordance with Rules 1 and 2 are that the "GO" and "NO GO" functional gages, the tools, and the fixtures are designed to their basic dimensions FREE OF CHARGE.

In fact, no engineering drawing ever was, is, or ever will be a drawing of a part. But, a drawing is, however, and must be, the "GO" and "NO GO" gage limits between which a part must fit. The question anyone who makes, checks, or uses drawings must ask is, "Are the drawings of the gages for the part correct?"

and not,

"Are the part drawings correct?"

Fixed Fastener Designs

In applications where features vary little in size, such as threaded holes, studs, and materials made of standard stock, feature positional tolerances must be selected and assigned with great care. These are similar to and usually are fixed fastener designs, as shown in Figure 18. One plate is a clearance hole design, whereas the other has one threaded hole and one fixed stud.

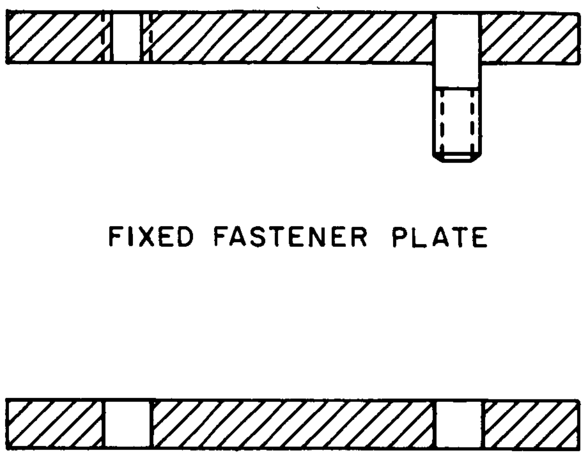


FIGURE 18

The two plates will be dimensioned and toleranced in the same manner as in Figure 13 except that the holes and studs are dimensioned and toleranced as in Figure 19. The fixed fastener size and positional tolerances must be assigned before the clearance hole specifications can be determined bacause the clearance hole size and positional tolerances first depend upon the fixed fasteners.

Note that the fixed feature positional tolerances must be selected by their required accuracy; in this case, a total of .100" maximum is considered functionally suitable

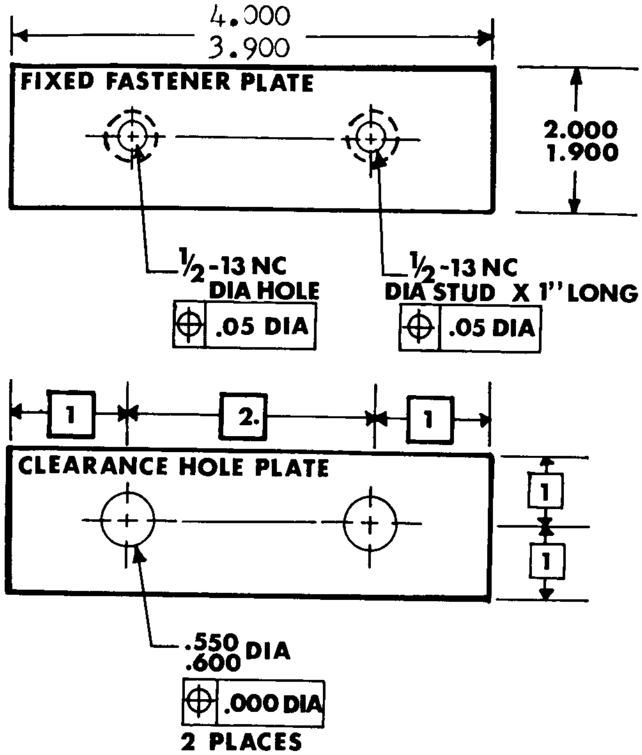


FIGURE 19

between mating parts. The fixed features are assigned a fixed .050" positional tolerance and the clearance hole size begins at the virtual fixed fastener size of .500 + .050 = .550". It can go to .600" dia. max. In effect, the clearance hole carries a variable positional tolerance beginning at ⌖ of .000" at Ⓜ and can go to .050" at Ⓛ . The total .100" tolerance zone must be equally or unequally divided between the mating features and assigned by the designer. In this case, the distribution is equal. In effect, the ∑Positional tolerances shall be equal to or less than ∑ Clearances.

Dowel Pin Designs

If the plates are doweled together with pressed-fit pins, the positional accuracy requires line-drilling. In this case, interchangeability with other plates is not possible because perfect alignment is required or ⌖ within .000" of the mating parts.

⌖, Ⓢ and Ⓜ Summary

Figure 20 shows the steps of applying Ⓜ and ⌖ .

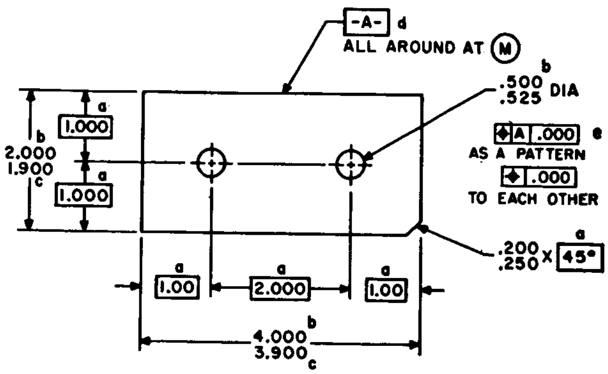


FIGURE 20

a. Place all dimensions of position into boxes to indicate them as BASIC and without tolerance. DIMENSIONS OF POSITION NEVER SHALL HAVE A TOLERANCE! Then chain dimension the position dimensions so as to add-up the related feature's Ⓜ size.

b. Show the dimensions of size as the limits of Ⓜ and Ⓛ .

c. Make sure that Ⓛ is placed below or after Ⓜ .

d. Add the datums to exclude or separate the nonfunctionally related features.

e. Add the feature control symbols with their appropriate tolerances. (For this design shown, the dimensions and tolerances of size adequately contol the form. Therefore, form tolerances are omitted.)

These five simple steps are all that is necessary to design with Ⓜ and ⌖ concepts.

Note that Ⓢ is not used to locate any feature at any time. Yet, Ⓢ is the most common form of dimensioning and tolerancing. Ⓢ is <u>never</u> the most economical and workable system for interchangeable fit.

Learning the ⌖ and Ⓜ method is not difficult, but the concept is different. It must be admitted, however, that to break the Ⓢ habit will be difficult, although to do so is vital to our personal, employer's, and National economic interests. It should be evident now that almost all tolerance zones could be at least doubled; and until this is done, we can never expect to substantially reduce the cost of products and at the same time specify better quality in our products. Could not a few pennies of this be tapped off the top to pay for ⌖ training and enforcement?

POSITIONAL ACCURACY VS COST

Figure 21 is a graph of positional accuracy versus % of costs.

The theory used to develop Figure 21 is, "As a target area increases, the cost of hitting the target decreases." True position is at the centerline intersection of the concentric tolerance zone. As the tolerance zone (allowable errors) varies, the cost of positioning varies directly by the square of tolerance diameter.

SHOP ACCURACY VS COST

A second correlation derived from Figure 21 is that of the capability of tooling from different classes of operations or shops. If the required precision of a product could be achieved with decreased shop precision or operator skill, the cost of producing a unit distance or area of accuracy decreases as you progress from shops of greater to lesser precision capability. In other words, design first for the accuracy that your product needs, but keep in mind that sheet metal work has a lower overhead cost than machine shop work. Even sheet metal shop work can cost more, however, if it is required to produce a degree of precision which is normally expected in other shops. We cannot design to have the National Bureau of Standard's gage-making shop accuracy in our products, and then expect low construction worker costs per unit length of accuracy.

GAGE TOLERANCES

A third correlation that Figure 21 provides is how tolerance zones are divided up in processing and inspection. Each gage in a production operation ordinarily is allowed 10% of the available tolerance zone, according to standard custom or need. If each of the eight gaging and process functions were assigned 5% as shown in Figure A, it is then logical to deduce that about 40% of the diameter or 64% of the tolerance area would be assigned to all the gages. This area is then lost for use by the operator who actually makes the feature on a part. However, if good quality control methods are used, these necessary gage tolerances indicate the need for optimizing designs with the broadest tolerances possible on the end-item drawings.

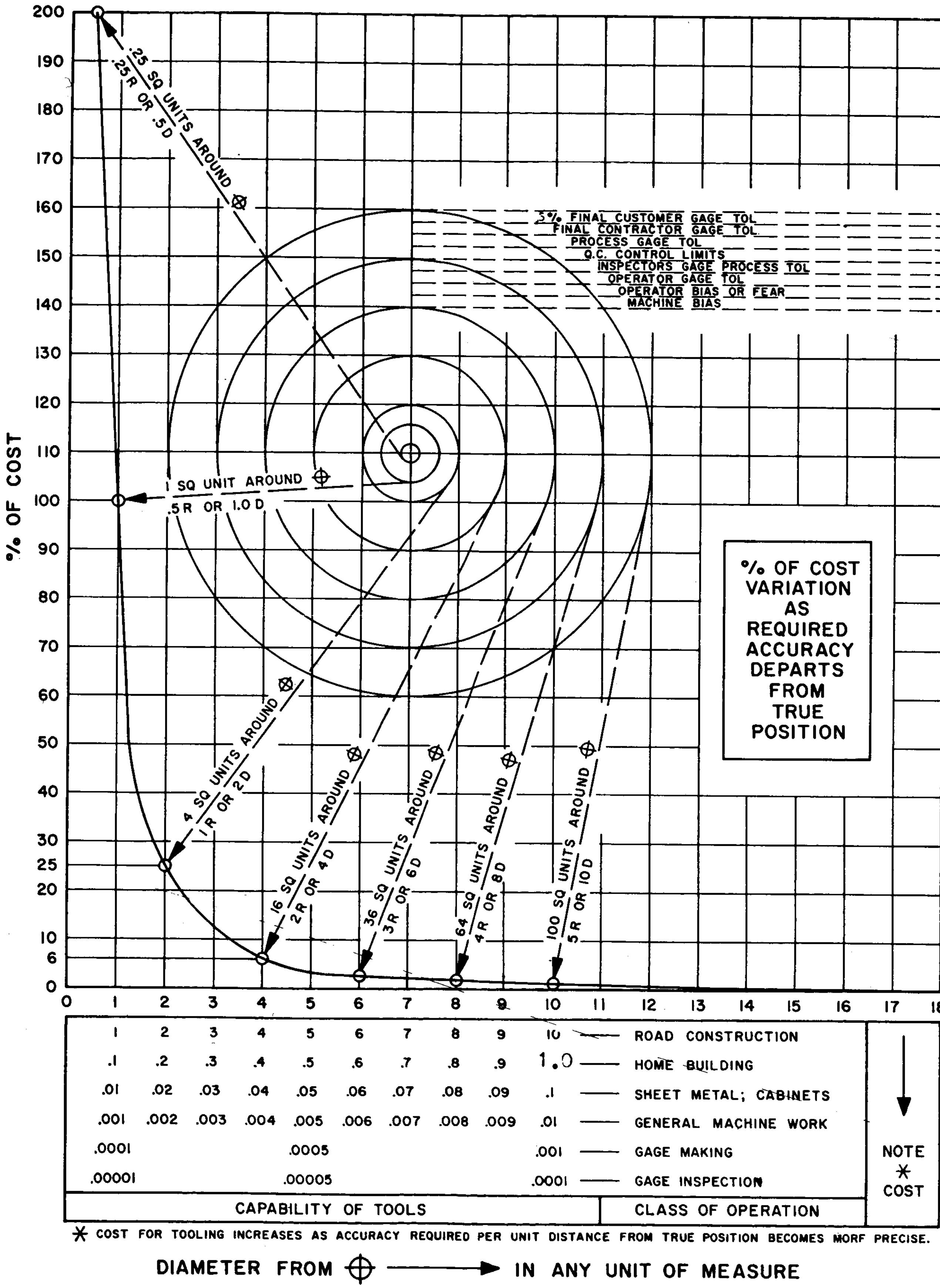

% OF COST
.25 SQ UNITS AROUND
.25 R OR .5 D
1 SQ UNIT AROUND
.5 R OR 1.0 D
4 SQ UNITS AROUND
1 R OR 2 D
16 SQ UNITS AROUND
2 R OR 4 D
36 SQ UNITS AROUND
3 R OR 6 D
64 SQ UNITS AROUND
4 R OR 8 D
100 SQ UNITS AROUND
5 R OR 10 D
5% FINAL CUSTOMER GAGE TOL
FINAL CONTRACTOR GAGE TOL
PROCESS GAGE TOL
Q.C. CONTROL LIMITS
INSPECTORS GAGE PROCESS TOL
OPERATOR GAGE TOL
OPERATOR BIAS OR FEAR
MACHINE BIAS
% OF COST VARIATION AS REQUIRED ACCURACY DEPARTS FROM TRUE POSITION
1 2 3 4 5 6 7 8 9 10 — ROAD CONSTRUCTION
.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 — HOME BUILDING
.01 .02 .03 .04 .05 .06 .07 .08 .09 .1 — SHEET METAL; CABINETS
.001 .002 .003 .004 .005 .006 .007 .008 .009 .01 — GENERAL MACHINE WORK
.0001 .0005 .001 — GAGE MAKING
.00001 .00005 .0001 — GAGE INSPECTION
CAPABILITY OF TOOLS
CLASS OF OPERATION
NOTE * COST
* COST FOR TOOLING INCREASES AS ACCURACY REQUIRED PER UNIT DISTANCE FROM TRUE POSITION BECOMES MORF PRECISE.
DIAMETER FROM ⊕ IN ANY UNIT OF MEASURE

FIGURE 21

THE SEVEN THIEVES OF PRODUCT VALUE:

This section attempts to identify and illustrate nonfunctional and misleading drafting concepts, a method for doing a worst-case tolerance analysis, and the recommended conversion steps from customary Ⓢ to Ⓜ and ⌖ drafting methods.

Seven common drafting concepts are thieves of product value. Because these concepts have no easy-to-use short names, let us design then as C1, C2, ---, C7. The seven concepts are:

C1. Bi-lateral Tolerancing from Nominal Dimensions of Feature Size.

C2. Bi-lateral Angular Tolerances from Nominal Degree Specifications.

C3. Tolerance Blocks for Unless Otherwise Specified Tolerances.

C4. Base Line Dimensioning (intended to prevent undesirable tolerance accumulation.)

C5. Centerlines Used as Datums.

C6. Tolerances for Dimensions of Position.

C7. Form Tolerances Used as Fit Specifications or Applied Beyond Feature Limits.

Figure 22 is a composite drawing illustrating these seven concepts and typifying most of today's mechanical design practices. These concepts steal from product value because they contribute little or no support to the actual functioning of a product, and their combined effect will convey misleading information to craftsmen and inspectors. Craftsmen and inspectors circumvent these concepts by ignoring them and by following only the basic design dimensions to the best of their ability. The products will usually work, but with "no-thanks" to these tolerancing concepts. The craftsman or producer can use the ambiguities and his subjective interpretations of these concepts to his own advantage however, when the processes produce inferior products and yet apparently still conform to the customer' drawing specifications. These drafting defects allow some products to be accepted which should be rejected; and ironically, allow other products to be rejected which should be accepted. As a result, we actually design-out good quality, design-in poor quality, and pay many times more than we should for our products.

Although these concepts occur in almost every set of mechanical drawings and are well established as principles intended to assure product quality, they exist because no one seems to question their validity. Industry has unwittingly harbored and paid hard cash for the wasteful consequences of these design customs. The added cost of these methods is far greater than we can realize or measure. Now that we feel the combined effects of inflation and high employment in a faltering economy, it is THE time to search for the causes of waste we can no longer afford.

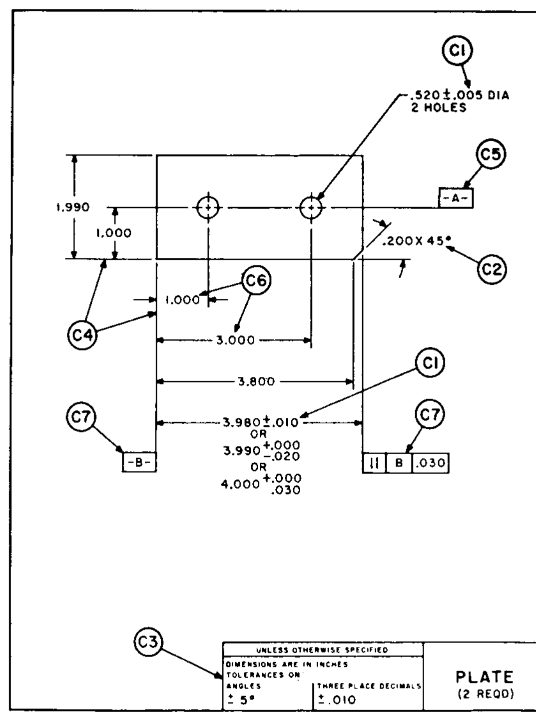


FIGURE 22

Figure 22 shows typical applications of these concepts, in composite form. A worst-case analysis that follows this section will demonstrate that the Figure 22 concepts do not adequately perform their functions.

For example:

a. C1/C6 combine to cause potential interference fits at assembly by 25% of the total tolerance zones. Ordinarily, this exceeds 50%.

b. C1 specifies that a hole smaller than .515 but greater than .500 diameter is a reject, even if it in fact perfectly located. Ⓜ and ⌖ concepts would accept these better quality holes.

c. C1 and C2 combine to produce ambiguous and redundant form and size tolerances for angles. Inspection must ignore this because it is unenforceable.

d. C3 is used when designers do not know how to apply functional tolerances or are afraid of forgetting to assign tolerances. In other words, C3 is a "tolerance block of fear and ignorance", which is seldom economical or workable.

e. As commonly applied, C4 at least doubles the tolerance accumulation between mating features. This doubles the required production precision and increases costs to make products fit.

f. When C5 establishes centerlines as datums, two questions arise: First, "From which feature is the center line established?"; Second, "If the feature is known, is the centerline established from Ⓜ or Ⓢ ?". As a result, craftsmen and inspectors must subjectively interpret or arbitrarily guess the datum center line locations.

g. C6 is NEVER functionally required. Only features can have tolerances of position. Features are placed relative to locations that are defined as perfect dimensions of position or ⌖ . (C6 is by far our greatest source of waste by specification.)

h. C7 typifies the most common misuse of form tolerances. If limits of size are met, the form tolerance is unnecessary. Almost all form tolerances fail this test, but the designers nevertheless impose an expensive and unnecessary inspection requirement.

Action towards correcting or eliminating these wasteful concepts can begin with positive drafting concepts. Positive improvement can be achieved only through the rules provided in the Standard ANSI Y14.5.

WORST CASE ANALYSIS EXAMPLE

A typical worst-case-tolerance-analysis of the Figure 22 lateral hole pattern would utilize the formula Σ Positional Tolerance shall be $\leq$ Σ Clearances.

a. A first step analysis easily shows that the plate lengths of 3.980, 3.990, or 4.000, including their tolerances, would fit the 4.000 long hole, Figure 11. (The reason for showing more than one length dimension for illustrating C1 is to show some common methods of specifying size.)

b. A second analysis of Figure 22 shows that the hole pattern worst-case of a <u>two plate assembly</u> is as follows for the features that must work together:

Plate	Dim.	Tolerances	Total
#1	1.000;	(+.010,-.010)=	.020
#2	1.000;	(+.010,-.010)=	.020
#1	3.000;	(+.010,-.010)=	.020
#2	3.000;	(+.010,-.010)=	.020
Positional		Tolerances =	.080

Min. Hole	Bolt Dia.		Clearance
.515	-.500	=	.015
.515	-.500	=.	.015
.515	-.500	=	.015
.515	-.500	=	.015
Clearances		=	.060

Therefore, the total virtual interference possible is .020, or .010 in any actual single assembly. Because of the + or - tolerancing method, we should

also note that the total "virtual design tolerances" usually result in a 1/2 actual error in the product. It is better to do a worst-case analysis using a total tolerances instead of calculating on the basis of all the pluses and then the minuses to get the actual interference at assembly. The total tolerance method that is developed above is very simple arithmetic; just remember that the actual interference is usually 1/2 the total and that all tolerance must be considered as a form of error. In addition, the base-line dimensioning restricts the tolerance accumulation to only 2 pairs of functionally related holes. If the .020 tolerance zone diagonals are considered, then the sum of the positional tolerances equals .028 X 4 or .112 inches; and over 50% of the tolerance zone becomes invalid if the hole sizes are .515" diameter.

Certainly it is agreed that if the minimum hole size became .528 instead of .515 diameter, or if the positional tolerances were reduced to $\pm$ .005 instead of $\pm$ .010 inches, no interference would occur; but the kind of error in this example only typifies most specifications. The .020" interference is 25% of the .080" positional tolerance zone; but more often than not, the total interference from the transition fit specification exceeds 50% of the positional tolerance zone (transition fit is defined as a tolerance zone that allows both interference and clearance fits within the specification).

To eliminate the interference, note that the positional tolerance must be halved in Figure 22, or the minimum hole size must be increased. Both tactics tighten tolerances, restrict processing options, and thereby increase costs. However, if Ⓜ and ⌖ are used with Zero Positional Tolerancing methods (as in Figure 15), the specifications will not only accept the Figure 22 holes, but will also accept any better located holes between .500 and .515 diameters. The hole size range is increased by 150% and the best quality fit becomes acceptable, whereas in Figure 22 it was considered a reject. These methods can be used on all drawings to specify better quality and reduce costs. Do not fear the "line-to-line-fit" of Zero Positional Tolerancing, because your drawing specifications presently allow interference fits. Actually, the tolerance zone near the line-to-line-fit will be used for inspectors and gage-making allowances.

Connector Applications

No product required interchangeability more than electrical connectors. Let us examine three connector designs to demonstrate the Y14.5 General Rules of Ⓜ , ⌖ , and Ⓢ . These designs and rules must meet three fundamental needs of all good specifications:

1. Functional End Production Design. (Includes Interchangeability)

2. Economical Processing.

3. Inspection to Assure Quality.

FORK AND BLADE CONNECTOR

In any mated connector, it is the size and position of both the contacts and their guiding features which are the related assembly features. Since all contacts must have interference between pins and sockets to work as a first condition, their fit is determined by a pin size that is greater than a mating spring-type hole to make contact pressure. The second condition is to assure that all guiding features are large enough and positioned accurately to prevent contact or circuit damage. Let us examine a blade and fork contact assembly, Figure 23, so that is functional, economical, inspectable, and tested by :

$\lessgtr$ P.T. $\leqslant \lessgtr$ CL

This contact assembly is dimensioned and toleranced using the methods of Figures 19 and 20.
SEE:

Fig. 23A - Plug Sub-Assembly
Fig. 23B - Receptacle Sub-Assembly
Fig. 23C - Gage for Plug
Fig. 23D - Gage for Receptacle

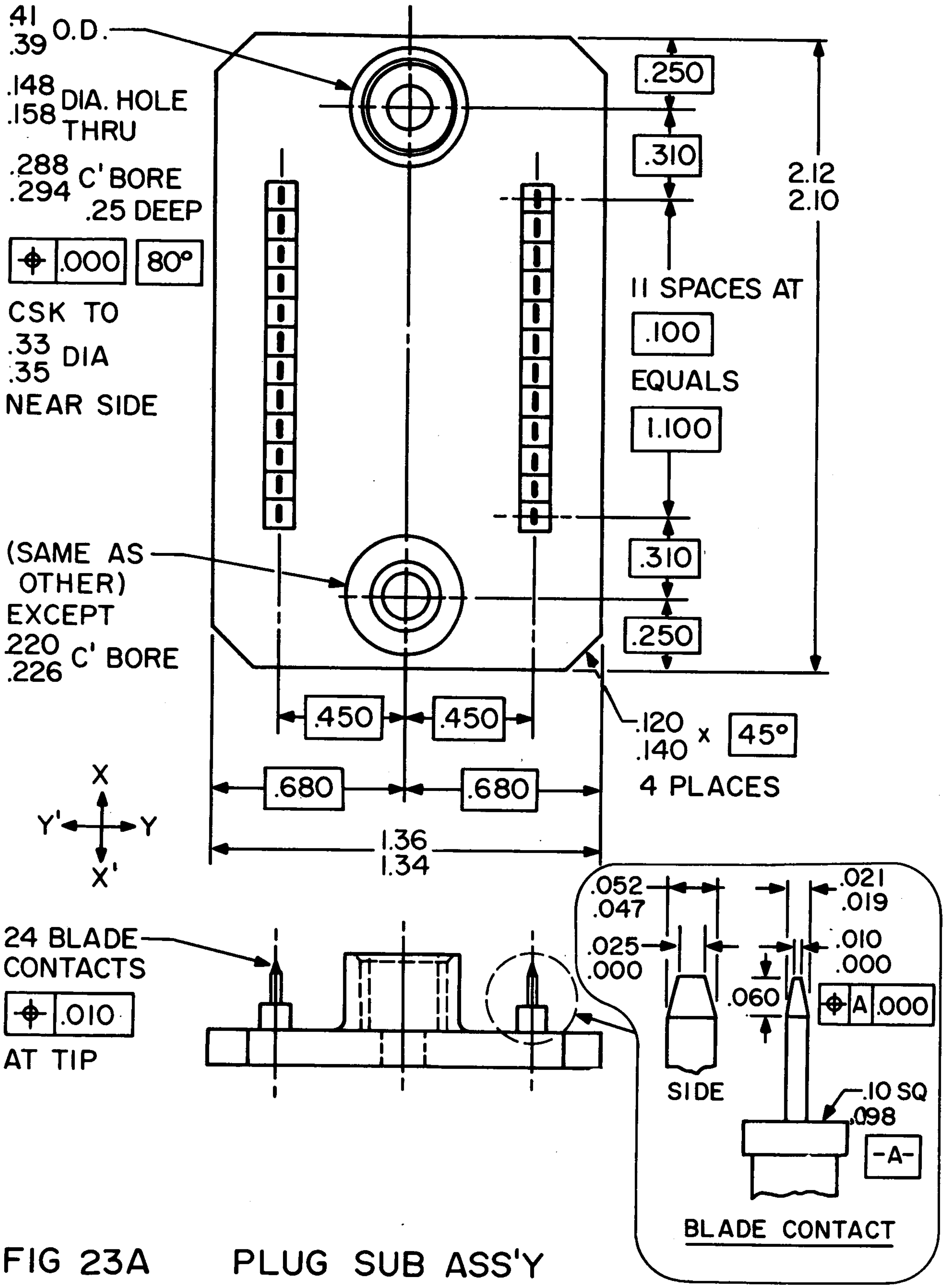


FIG 23A PLUG SUB ASS'Y

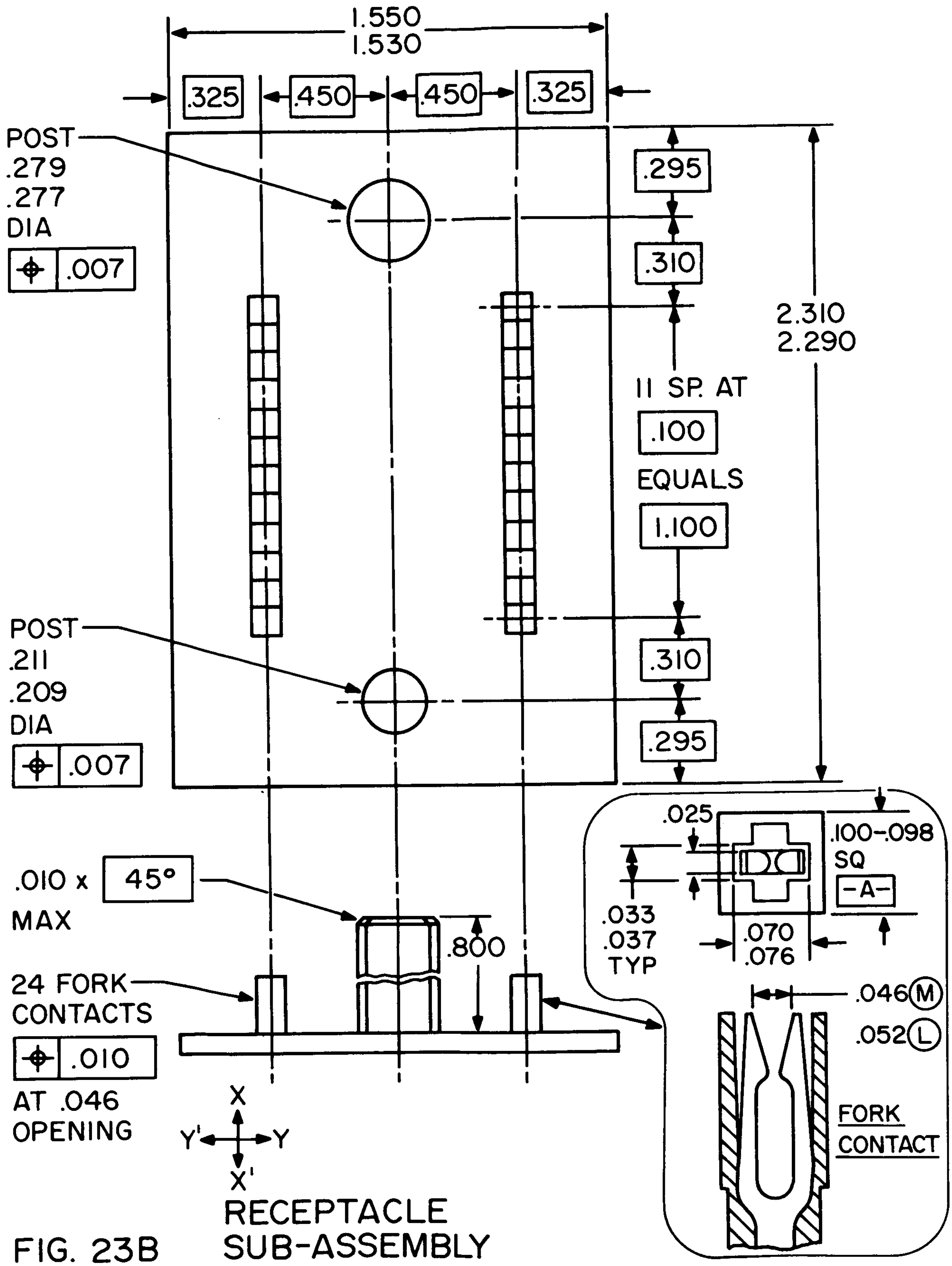


FIG. 23B RECEPTACLE SUB-ASSEMBLY

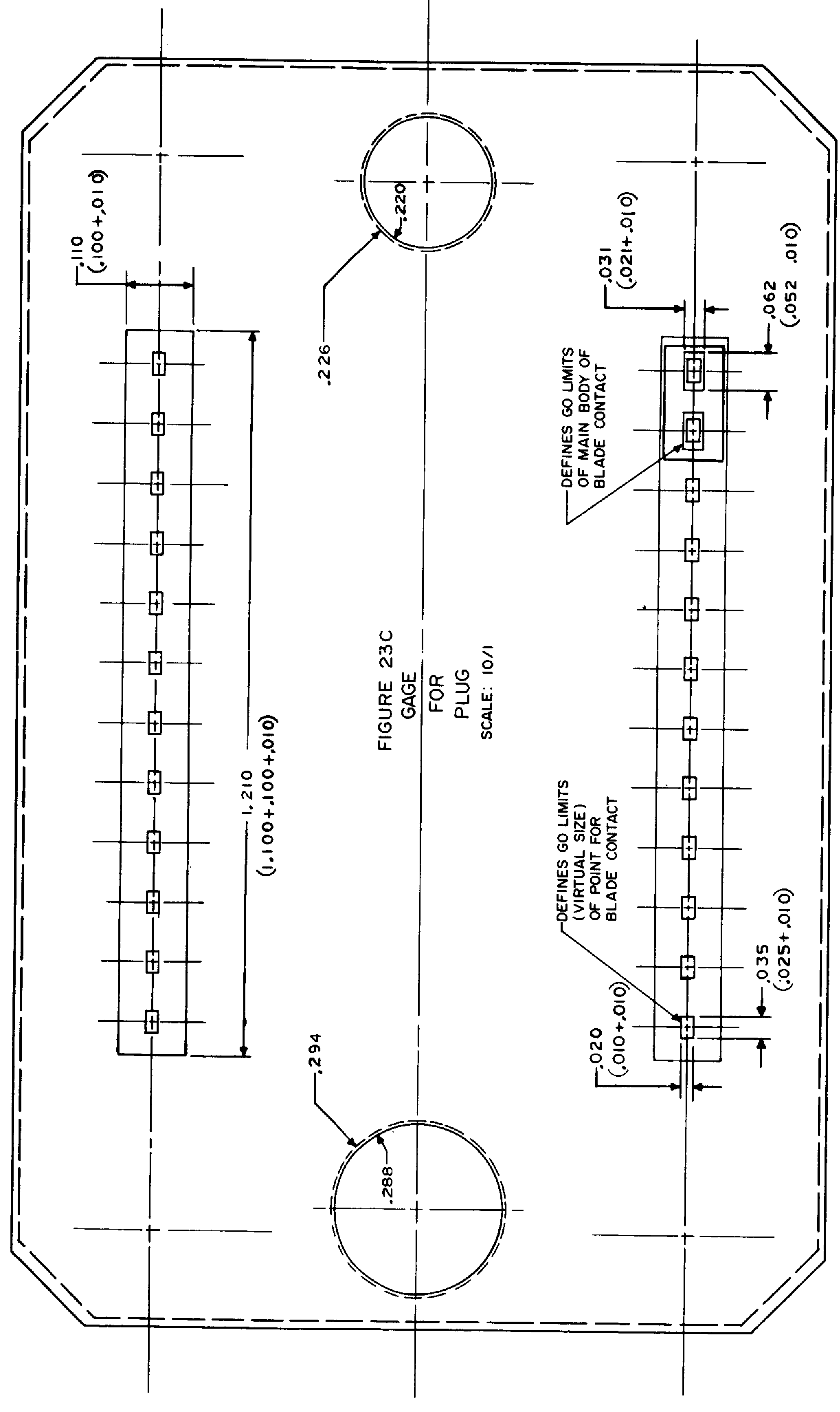


FIGURE 23C
GAGE
FOR
PLUG
SCALE: 10/1

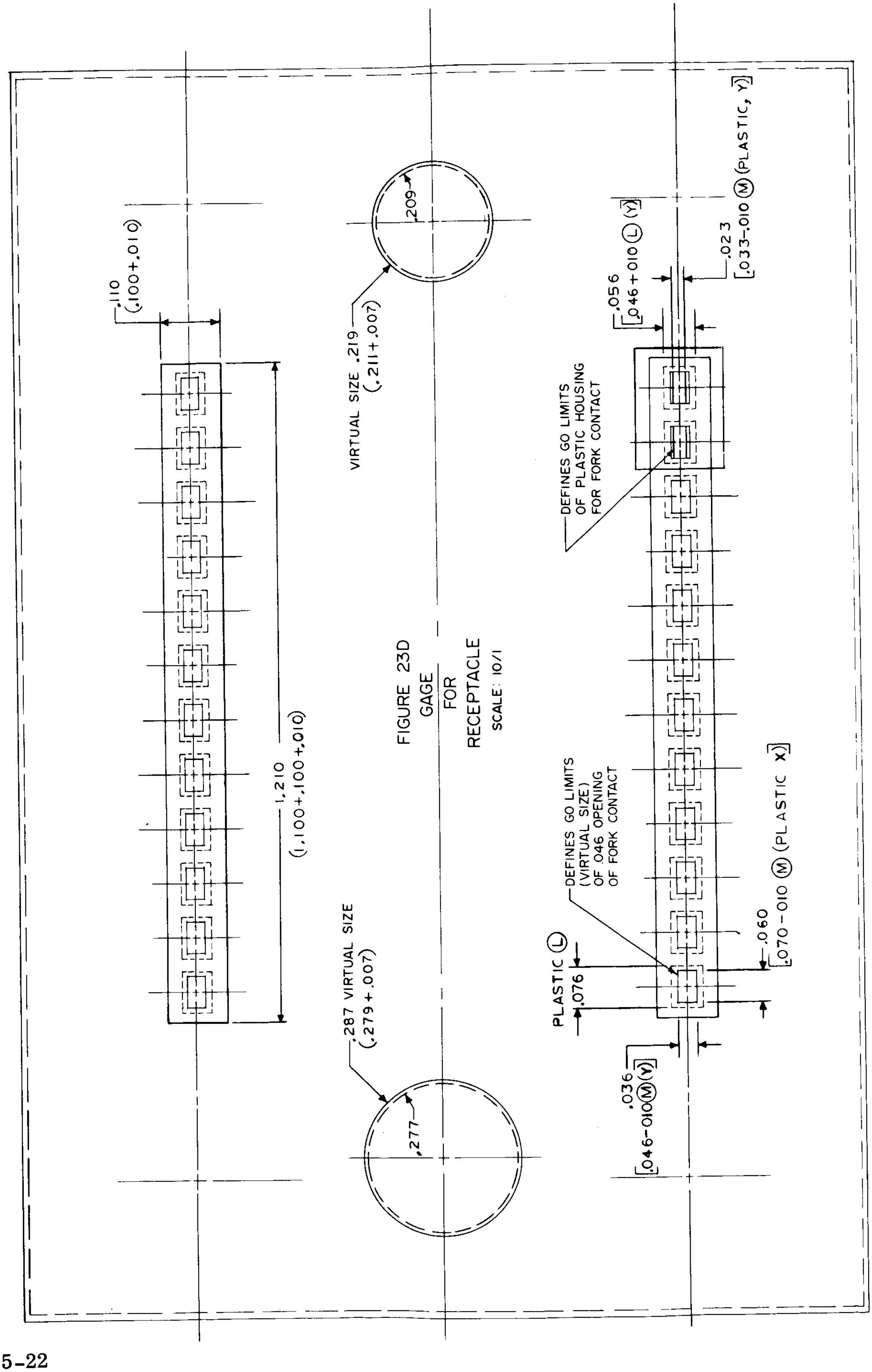


FIGURE 23D
GAGE
FOR
RECEPTACLE
SCALE: 10/1

WORST CASE ANALYSIS OF FORK AND BLADE CONNECTOR

The fork and blade connector of Figure 23 is a functional end product design because any combination of plugs and receptacles will intermate. Two methods prove this.

The first is to superimpose the gages 23C and 23D one above another using transparent paper. This "paper gage" will show that the point of the blade will always enter the .046 opening of the fork. The maximum misalignment would be when the guide pins and guide pin holes are at L plus their positional tolerance and the points are at their GO limits.

The GO limits are a combination of M and positional tolerance called, <u>Virtual Condition</u>. This application is a typical "fixed fastener" application.

The analytical worst-case analysis is the second method of proof. The .046 M is the critical "bulls-eye" that must be hit in the fork contact. The arrow is the .010 M point on the blade. Therefore, we must show that ΣPT $\leq$ ΣCL. The Σ CL equals .046 - .010 or .036.

The Σ PT equals:

.046 PT	= .010
.C'Bore Tol.	= .006
.C'Bore PT	= .000
Allowance Between POST & C'Bore	= .001
POST PT	= .007
POST Tol	= .002
TIP PT	= .010
PT	= .036

Therefore, the Σ PT = Σ CL.

Note that many other combinations are possible by assigning tolerances by using a different distribution, as long as the totals are the same. However, a new gage and specification would have to be made for each combination. This shows why assigned tolerances run the risk of rejecting good parts and may have to be changed if the actual production needs dictate.

The total cumulative tolerance in this system is large, but it is controlled. This control is used only to assure that the point of each of the 24 contacts enter the fork. From then on, they are guided into their spring loaded positions by their feature contours.

The above blade and fork connector was analysed only in the "Y" direction, which for this connector style is most critical. It is in the "Y" direction that problems occur when the blade misses the fork opening. It is this damage that this analysis trys to prevent.

P.C. EDGEBOARD CONNECTOR

Printed circuits and their edgeboard connectors sometimes fail by splitting the connector in half, open circuits, and short circuits. When a board is wider than the connector hole, the connector splits or cracks. When the board is too narrow, the hole too wide, or the contacts are off position, opens or shorts occur.

Figure 24 shows how a P.C. board and edgeboard connector are specified to prevent the above failures. High density contacts, .050" spacing, have a great tendency to fail. The bigger contacts and spacing reduce the chance of failure.

The worst-case analysis for Figure 24 is as follows:

A. Check for Shorts.

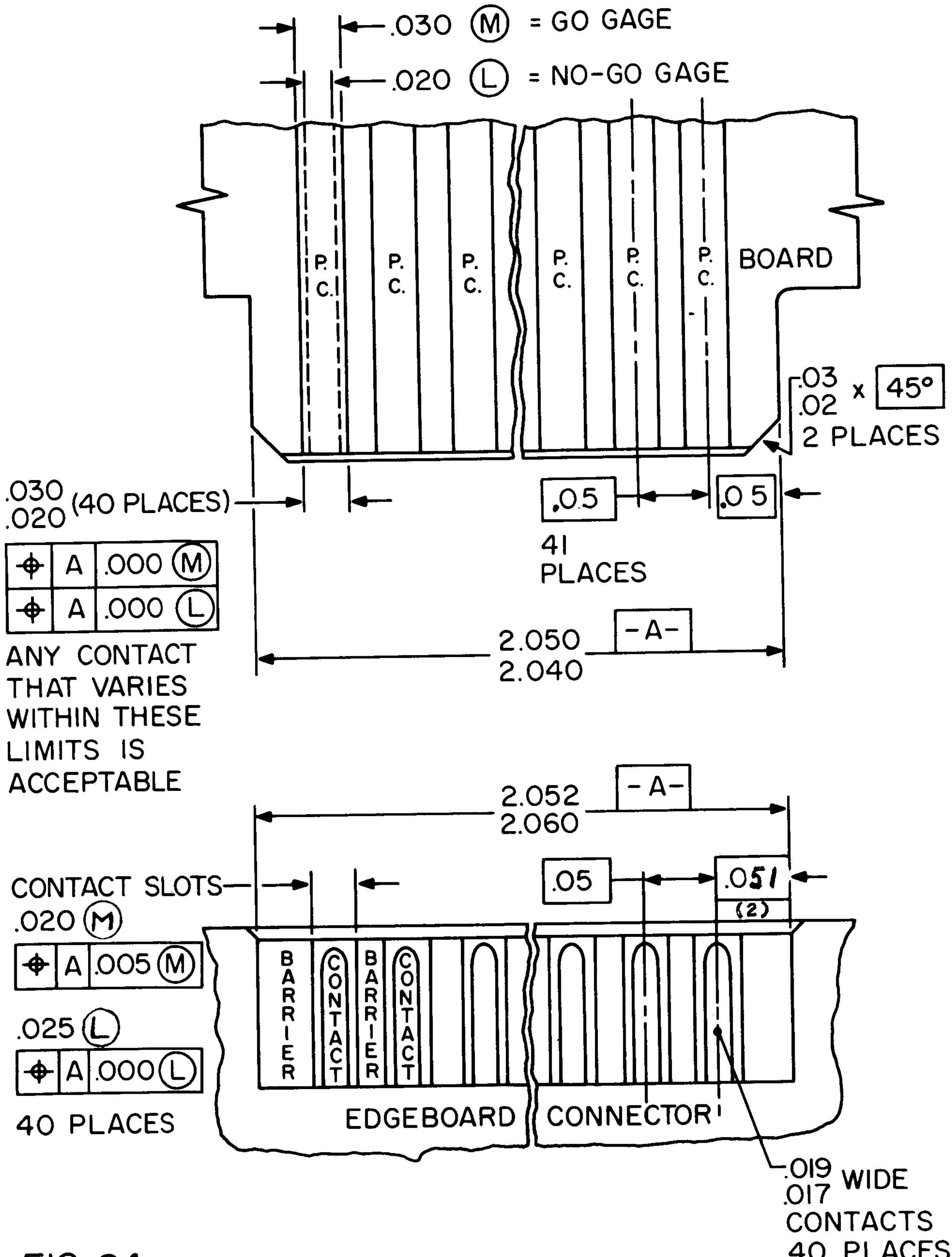
The Σ CL are:

P.C. contact space		= .050
Connector slot space		= .050
Total space available		= .100
P.C. width	= .030	
Slot width	= .025	
Tot. Width	= .055	- .055
Total Clearance or ΣCL		= .045

The Σ PT are:

L Board - L Connector	=-.020
Σ PT < ΣCL by	.025

This means that adjacent contacts may come close a short circuit within ½ of .025" or .0125".



.030 (M) = GO GAGE
.020 (L) = NO-GO GAGE
P. C.
P. C.
P. C.
P. C.
P. C.
P. C.
BOARD
.03
.02 x 45°
2 PLACES
.030
.020 (40 PLACES)
.05
.05
41 PLACES
⌖ | A | .000 (M)
⌖ | A | .000 (L)
ANY CONTACT THAT VARIES WITHIN THESE LIMITS IS ACCEPTABLE
2.050
2.040
-A-
2.052
2.060
-A-
CONTACT SLOTS
.020 (M)
⌖ | A | .005 (M)
.025 (L)
⌖ | A | .000 (L)
40 PLACES
.05
.051
(2)
BARRIER
CONTACT
BARRIER
CONTACT
EDGEBOARD CONNECTOR
.019
.017 WIDE
CONTACTS
40 PLACES

FIG 24

B. Check For Opens.

Σ Cl are:

Ⓛ PC contact width	= .020	
Ⓛ connector contact width	= .017	
		.037

Σ PT

Ⓛ PT PC contact	= .000	
Ⓛ PT Con. Cont. (.025 - .017)	= .008	
Ⓛ PC board - Ⓛ connector hole	= .020	
Total PT	= .028	-.028
Σ PT < Σ CL by --------------		.009

This means that the minimum contact overlap is ½ of .009 or .0045.

C. Check for Splitting Force.

Ⓜ Board Width - Ⓜ Connector Hole Width = .002" Clearance @ Ⓜ .

If a board is inserted straight into the connector, the force in the X direction is zero.

The gages for Figure 24 would like it is shown on the PC contact marked with the .030 GO and .020 NO-GO limits.

RACK AND PANEL CONNECTOR

Rack and panel connectors sometimes fail because the contacts bend or are pushed back out of their spring retention clips. The pins and sockets can butt each other on their leading edges when there is misalignment. To achieve a forgiving design, the chamfers on pins and sockets must be equal to or greater than the positional tolerances.

See:

Figure 25A (Plug)
Figure 25B (Receptacle)
Figure 25C (Plug Gage)
Figure 25D (Receptacle Gage)

Note the use of contour or profile tolerancing at Ⓜ . This simplifies the complex contours of the interface between the shells. The receptacle will always be larger than the plug and the plug will always be smaller. At the corner radii, the tolerance becomes broader because they are less critical than the pads for controlling contact position.

The pin and hole positional tolerances for the contacts also become tighter when the Ⓛ of the shells would produce greater misalignment than the shells at Ⓜ .

The worst-case analysis for Figure 25 is as follows:

Let us use the #20 contact of which there are 25. The other two sizes are 8 large coax and 4 - #16 contacts, (their analysis would be similar).

The #20 pin is .041 Ⓜ dia. and it has a .011 Ⓜ flat on its tip. (REF: MIL-C-83723/33). The chamfered opening in Plug 25A is .130 Ⓜ to receive the #20 pin.

Therefore Σ CL is:
.130 (Bull's eye) - .011 flat = .119
(Note that the #20 socket opening (chamfer) is protected by the .052 Ⓛ "closed entry" plug design).

Σ PT:

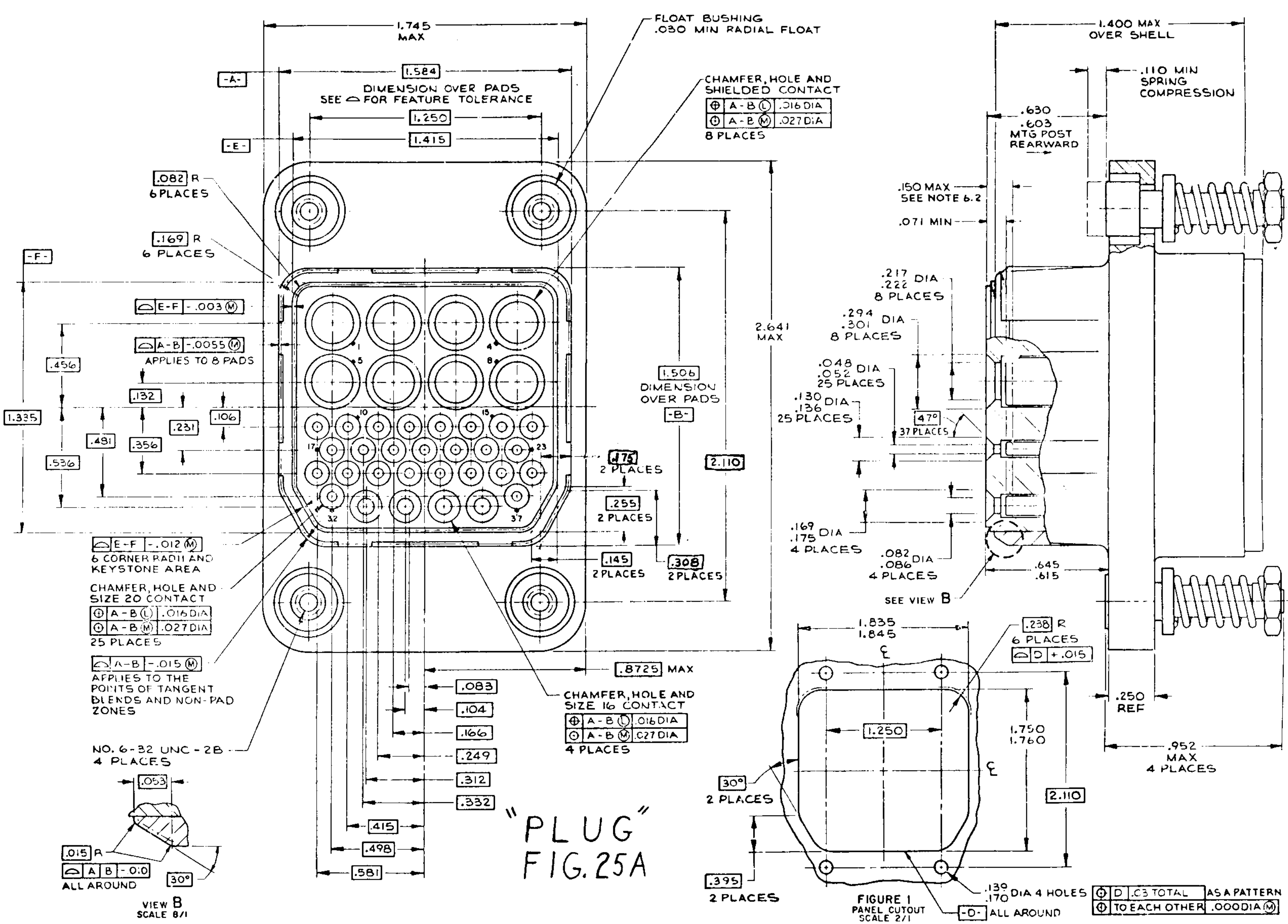
Plug Hole PT	= .027 @ Ⓜ	
1.585 Ⓜ Recp. - 1.584 Ⓜ Plug	= .001 Allowance	
#20 Pin PT	= .057 @ Ⓜ	
Σ PT	= .085	-.085
Total Clearance	=	.034

Observe that when the shells are at Ⓛ , the .011 for each PT is subtracted to compensate for the added mispositioning.

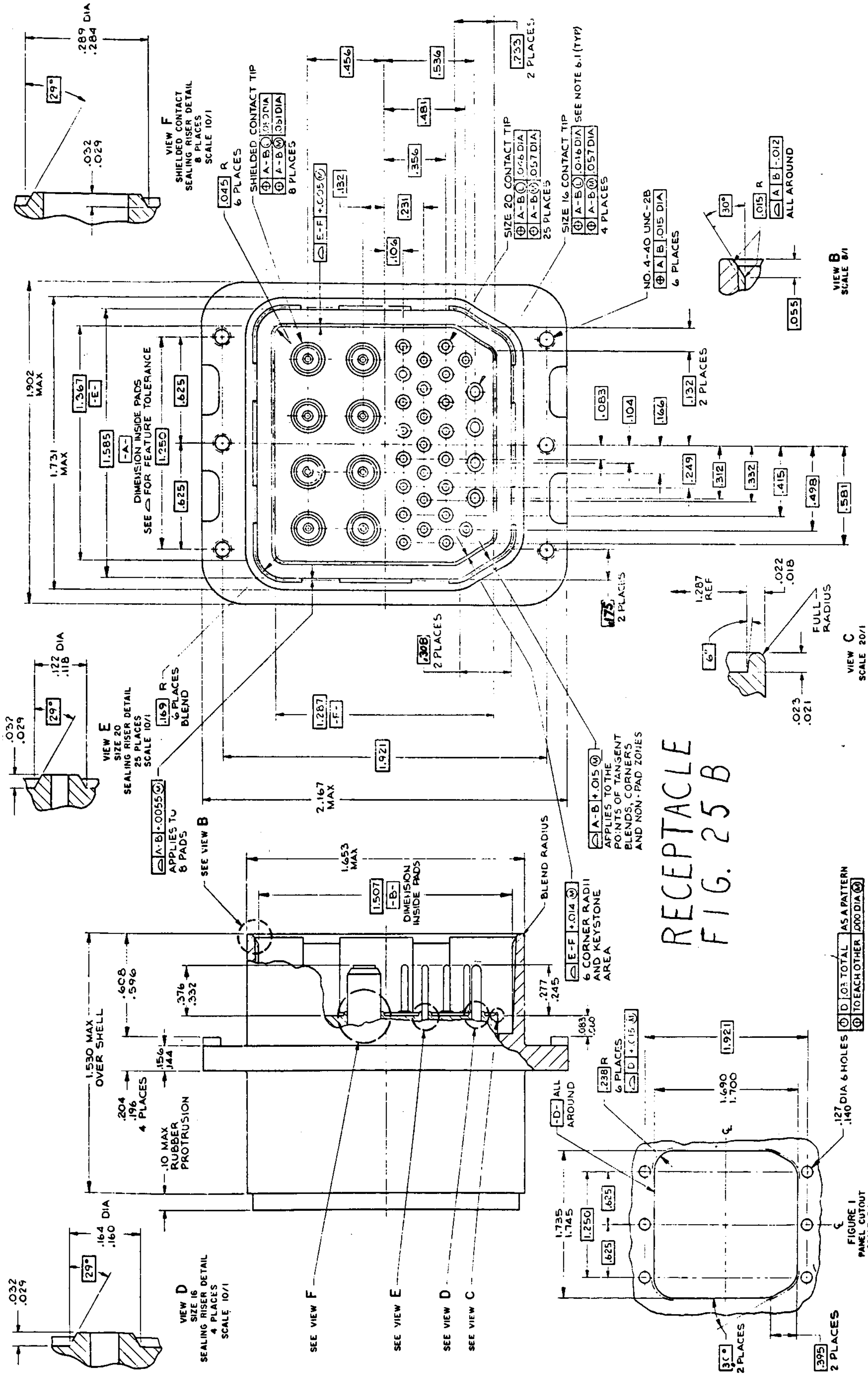
EXISTING SPEC. ANALYSIS

Let us analyse one of the existing connector specifications that is actually one of the better specs. of today. However it does:

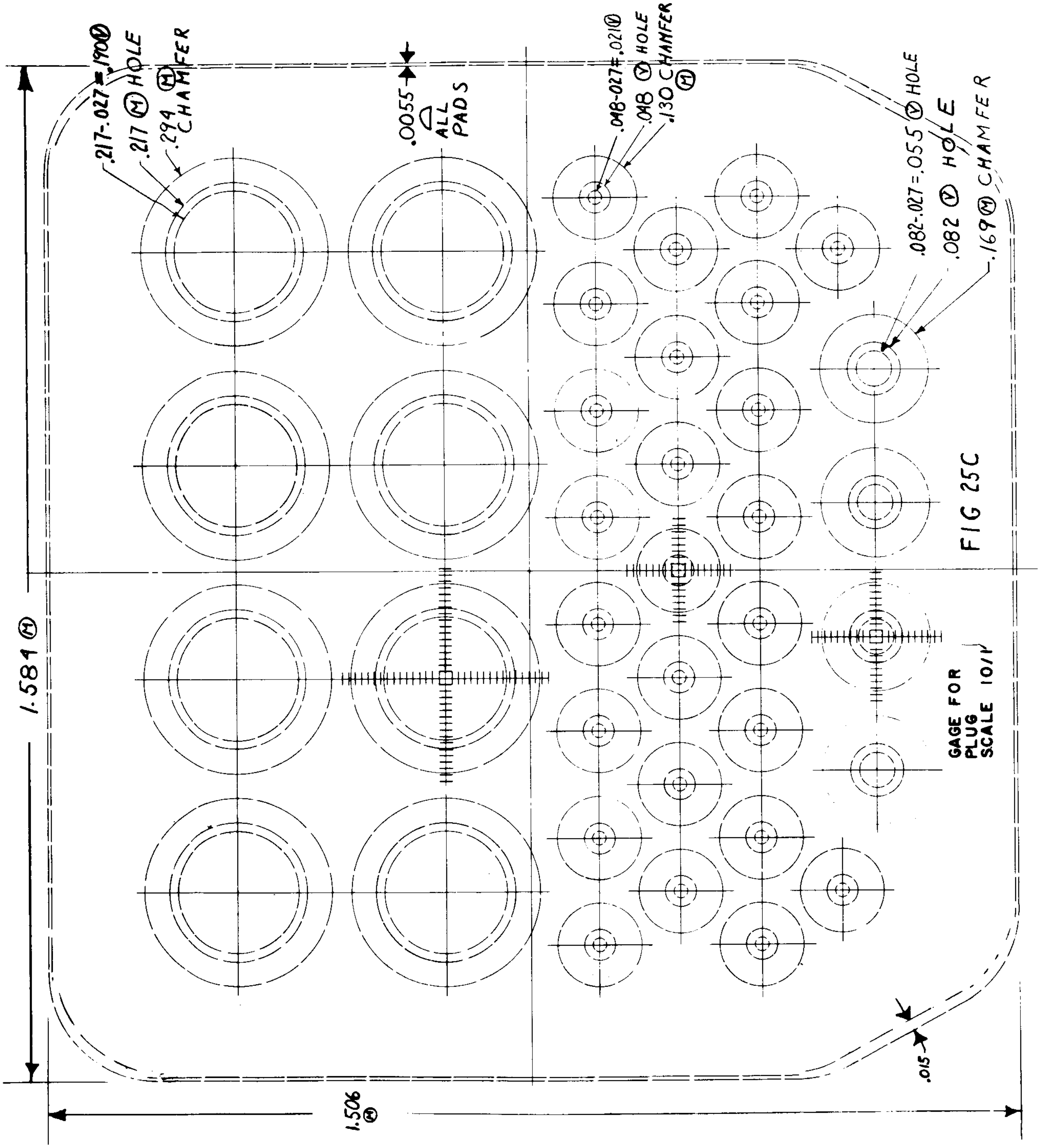
1. Reject quality parts.
2. Accept poor quality parts.
3. Impose unnecessary tolerances.


1.745 MAX
1.584
DIMENSION OVER PADS SEE ⌓ FOR FEATURE TOLERANCE
1.250
1.415
-A-
-E-
-F-
FLOAT BUSHING .030 MIN RADIAL FLOAT
CHAMFER, HOLE AND SHIELDED CONTACT
⊕ A-B Ⓛ .016 DIA
⊙ A-B Ⓜ .027 DIA
8 PLACES
.082 R 6 PLACES
.169 R 6 PLACES
⌓ E-F -.003 Ⓜ
⌓ A-B -.0055 Ⓜ APPLIES TO 8 PADS
.456
.132
.231
.106
1.335
.481
.356
.536
2.641 MAX
1.506 DIMENSION OVER PADS
-B-
2.110
.175 2 PLACES
.255 2 PLACES
.145 2 PLACES
.308 2 PLACES
⌓ E-F -.012 Ⓜ 6 CORNER RADII AND KEYSTONE AREA
CHAMFER, HOLE AND SIZE 20 CONTACT
⊕ A-B Ⓛ .016 DIA
⊙ A-B Ⓜ .027 DIA
25 PLACES
⌓ A-B -.015 Ⓜ APPLIES TO THE POINTS OF TANGENT BLENDS AND NON-PAD ZONES
NO. 6-32 UNC-2B 4 PLACES
.8725 MAX
.083
.104
.166
.249
.312
.332
.415
.498
.581
CHAMFER, HOLE AND SIZE 16 CONTACT
⊕ A-B Ⓛ .016 DIA
⊙ A-B Ⓜ .027 DIA
4 PLACES
.053
.015 R
⌓ A B -0.0 ALL AROUND
30°
VIEW B SCALE 8/1
1.400 MAX OVER SHELL
.110 MIN SPRING COMPRESSION
.630 .603 MTG POST REARWARD
.150 MAX SEE NOTE 6.2
.071 MIN
.217 .222 DIA 8 PLACES
.294 .301 DIA 8 PLACES
.048 .052 DIA 25 PLACES
.130 .136 DIA 25 PLACES
47° 37 PLACES
.169 .175 DIA 4 PLACES
.082 .086 DIA 4 PLACES
.645 .615
SEE VIEW B
.250 REF
.952 MAX 4 PLACES
1.835 1.845
.238 R 6 PLACES
⌓ D + .015
1.250
1.750 1.760
2.110
30° 2 PLACES
.395 2 PLACES
FIGURE 1 PANEL CUTOUT SCALE 2/1
.139 .170 DIA 4 HOLES
-D- ALL AROUND
⊕ D .03 TOTAL AS A PATTERN
⊕ TO EACH OTHER .000 DIA Ⓜ

"PLUG"
FIG. 25A



RECEPTACLE
FIG. 25B



.217-.027=.190 V
.217 M HOLE
.294 M CHAMFER
.0055 ALL PADS
.048-.027=.021 V
.048 V HOLE
.130 CHAMFER M
.082-.027=.055 V HOLE
.082 V HOLE
.169 M CHAMFER
GAGE FOR PLUG SCALE 10/1
1.581 M
1.506 M
.015

FIG 25C

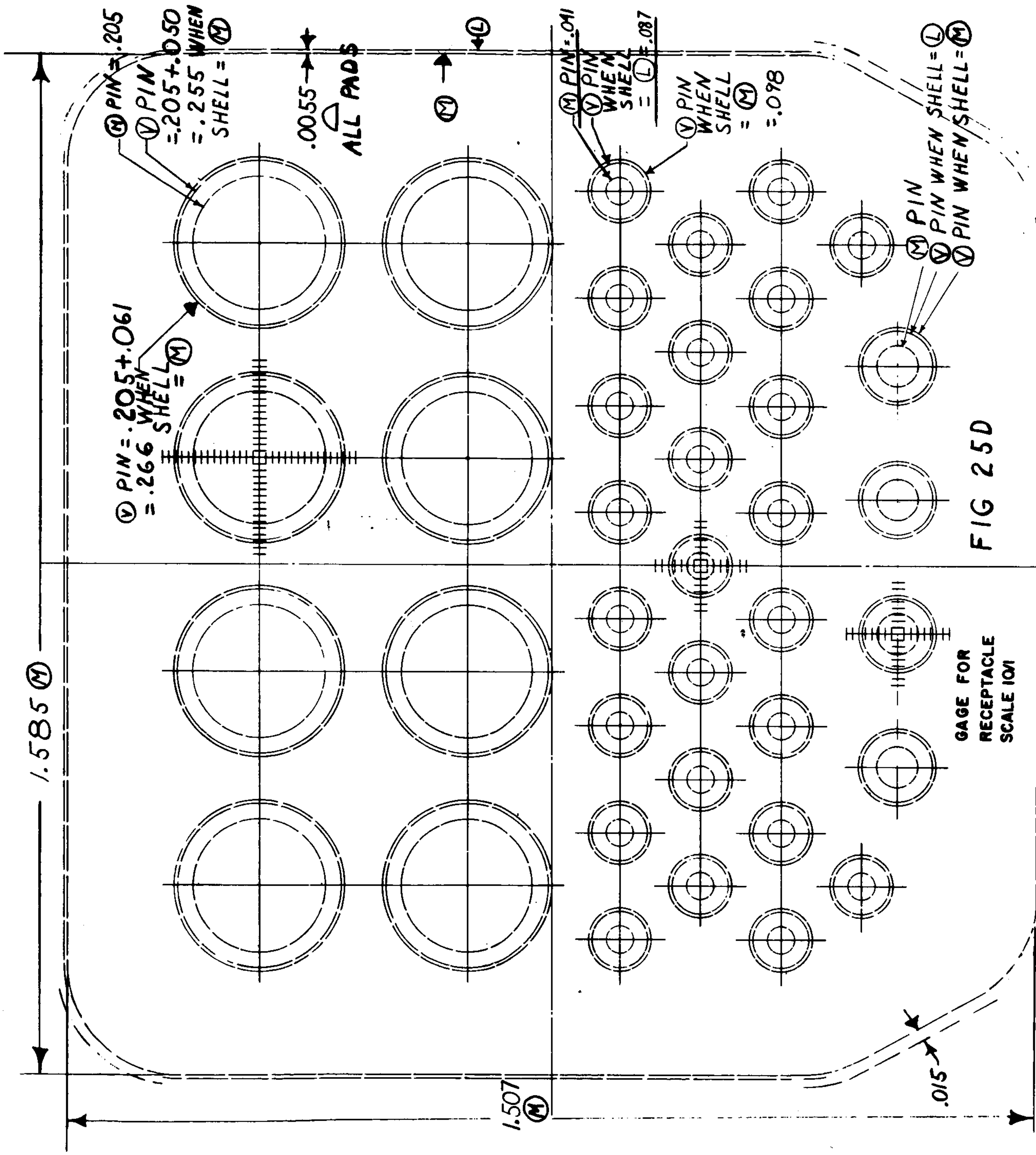

1.585 Ⓜ
1.507 Ⓜ
Ⓜ PIN = .205
Ⓥ PIN = .205 + .050 = .255 WHEN SHELL = Ⓜ
.0055 ALL PADS
Ⓜ
Ⓛ
Ⓥ PIN = .205 + .061 = .266 WHEN SHELL = Ⓜ
Ⓜ PIN = .041
Ⓥ PIN WHEN SHELL = Ⓛ = .087
Ⓥ PIN WHEN SHELL = Ⓜ = .098
Ⓜ PIN
Ⓥ PIN WHEN SHELL = Ⓛ
Ⓥ PIN WHEN SHELL = Ⓜ
GAGE FOR RECEPTACLE
SCALE 10/1
.015

FIG 25D

A. Figure 26A and 26B are Plugs and Receptacles to MIL-C0081511D. (Analysis is for #20 Contact.)

"Y" (M)	-	#20 pin flat	=	CL
.080	-	.016	=	.064

Σ PT:

(L) "A" Recp. - (L) "A" Plug	=	.014
PT of pin (Fig. 26C)	=	.021
PT of socket (Fig. 26C)	=	.018
"C" concentricity of plug	=	.008
"C" concentricity, recp.	=	.010
Total PT	=	.071

The interference is .064 - .071 or .007. If the concentricity is not counted, then there is a clearance of .011 which is O.K. But why specify a concentricity that is equal to the limits of size?

If General Rule #1 actually controls the size and form tolerance of the shells, then the "C" concentricity tolerances are redundent. The concentricity tolerances can only exceed the (M) if proper warning is given directly as prescribed on Page #36 of ANSI Y14.5.

It would be correct to specify "C" dia. with a zero PT, and, assign .032 PT to each pin and socket. This would broaden the tolerances and eliminate the concentricity spec., which requires a dial indicator inspection.

Note the 4 holes of .126/.116. If they are to receive a #4 screw(.112 dia.) the PT of .010 for the pattern would leave a .006 interference fit to the tapped holes that must mount the connector, if the tapped holes could be perfectly located.

The analysis is:
.116 - .010 = .106 virtual size.
-.112 + .106 = .006 interference fit.
(The PT of the holes to each other is missing.)

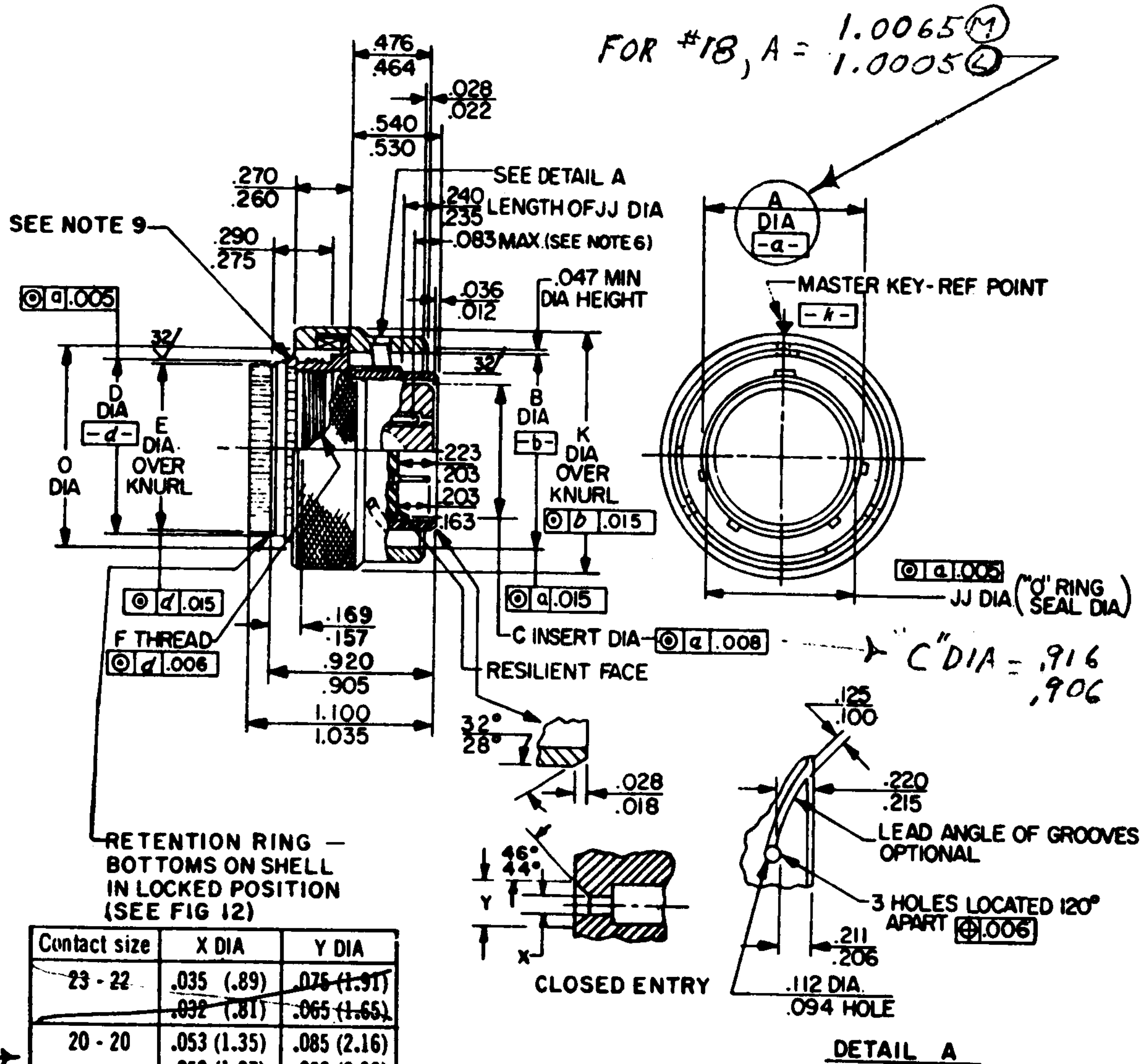
In summary:

All of the form tolerances of concentricity and symmetry are unnecessary restrictions that would be controlled by true position and maximum material condition rules #1 and #2. The only place that concentricity might be used is on the gasket seal to give a uniform sealing effect.

If the "G" width were asymmetric to a greater degree than the .016, we could chop off the wider side, but this would not improve the fit.

If the "C" dia is at (L) (.906), and would be eccentric on the plug by .010, it would be rejected, and yet it would be a useable quality plug.

The .116 holes would cause an interference fit, but this spec. would accept them if they were off position by the .010 tolerance which causes an interference fit.

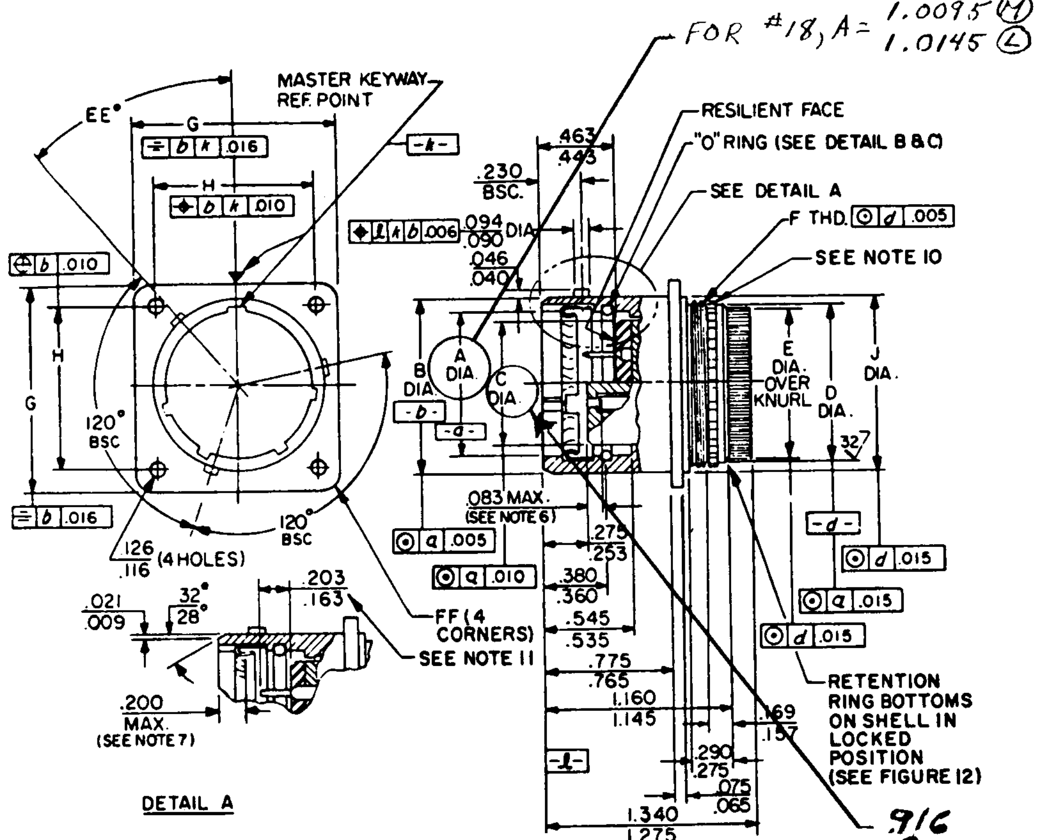


Contact size	X DIA	Y DIA
~~23 - 22~~	~~.035 (.89)~~ ~~.032 (.81)~~	~~.075 (1.91)~~ ~~.065 (1.65)~~
20 - 20	.053 (1.35) .050 (1.27)	.085 (2.16) .080 (2.03)
~~16 - 16~~	~~.077 (1.96)~~ ~~.074 (1.88)~~	~~.108 (2.74)~~ ~~.103 (2.62)~~
~~12 - 12~~	~~.130 (3.30)~~ ~~.126 (3.20)~~	~~.170 (4.32)~~ ~~.166 (4.22)~~

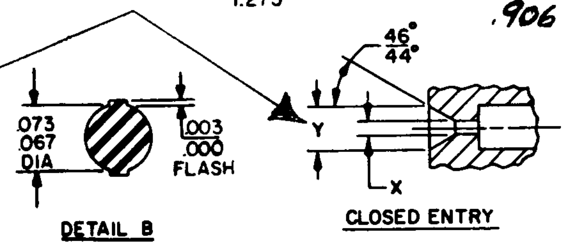
FIG. 26A

Connector, plug, electrical, (Series 2).

FOR #18, A = 1.0095 (M) 1.0145 (L)



Contact size	X DIA	Y DIA
23 - 22	.035 (.89) .032 (.81)	.075 (1.91) .065 (1.65)
20 - 20	.053 (1.35) .050 (1.27)	.085 (2.16) .080 (2.03)
16 - 16	.077 (1.96) .074 (1.88)	.108 (2.74) .103 (2.62)
12 - 12	.130 (3.30) .126 (3.20)	.170 (4.32) .166 (4.22)

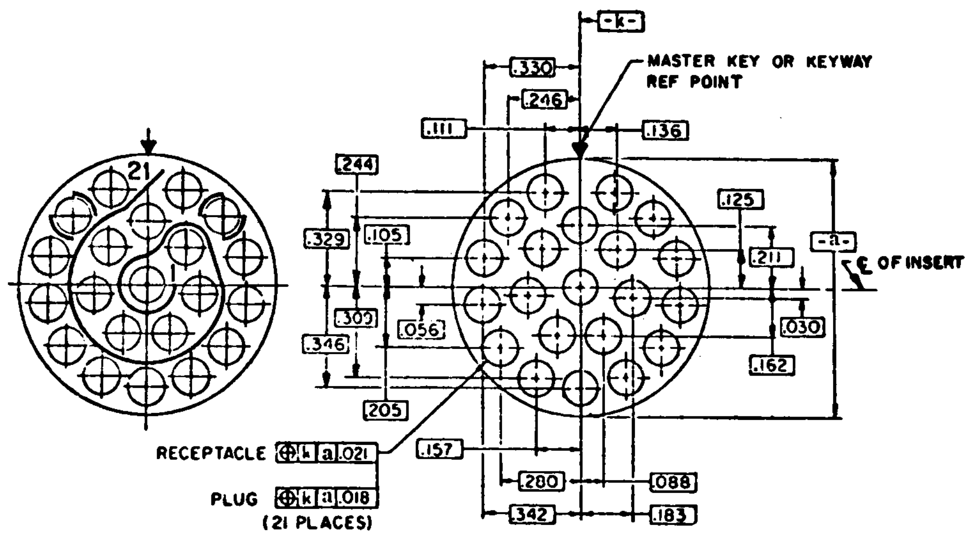


THE FLAT ON A #20 PIN IS .016 (M).

FIG. 26B

Connector, receptacle, electrical, flange mount (series 2).

FED. SUP CLASS
5935



CODE F03 INSERT ARRANGEMENT 18-21, SERVICE RATING I, 21 SIZE 16-16 CONTACTS

FIG 26C

REVISED (A) FOR CHANGES SEE SHEET 1

APPROVED 5 JUNE 1970

1964

P.A. NAVY-AS Other Cust ARMY-EL AF-17	International Interest	TITLE INSERT ARRANGEMENTS, MIL-C-81511 ELECTRIC CONNECTOR, SIZE 18	MILITARY STANDARD MS 3430
Procurement Specification MIL-C-81511		SUPERSEDES: MIL-C-81511 12	SHEET 3

CONCLUSION

In the beginning we asked, "WHY Ⓜ, Ⓛ, ⌖, Ⓢ ?". It was shown that 3 GENERAL RULES control the fit, quality, cost, and dynamic performance of our specifications and products. Each cannot be used in place of the other, but each has its own specific purpose. No other method, whether it is common or customary, is an economic or functional substitute.

The resistance that these General Rules receive is, "This is new and no one understands them, so we use the common accepted custom of bilateral tolerances to nominal dimensions". (This always implies regardless of feature size principles which give transition fits and other expensive product tolerances.)

If the above is to be the situation, let us ask the question, "MUST WE USE CUSTOMARY PRACTICES THAT ARE WRONG THAT PEOPLE UNDERSTAND, OR SHALL WE USE THE RULES THAT FEW UNDERSTAND, BUT ARE CORRECT?".

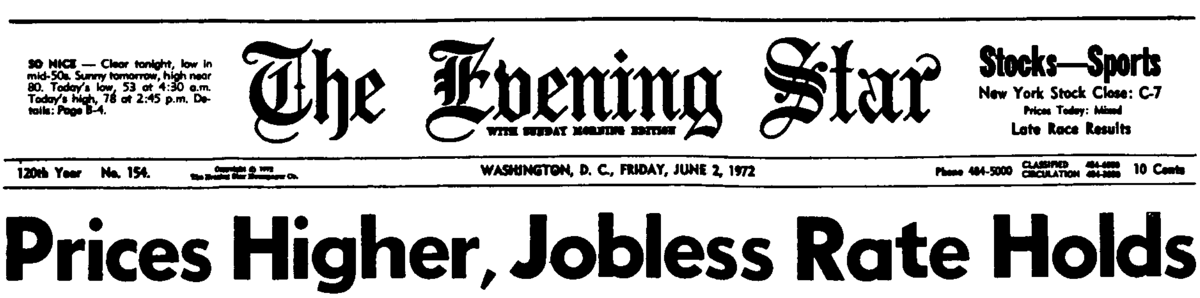
All that must be learned are:

1. 3 General Rules from Page 3.
2. 5 format steps shown on Page 11.
3. Test our designs by using: $\nleq$PT $\leq$ $\nleq$ CL.

If we learn the above, we can make a great contribution towards abolishing this kind of headline.

These rules were used by our forefathers to help create the 19th Century American Industrial Revolution by perfecting interchangeable manufacture of products. All that we must do is to is to REDISCOVER the principles of interchangeability so that our specifications are correct. Who teaches them or knows them today? If the specification is wrong, our costs and selling prices will be wrong, in spite of all else that we, our company, or our Government might do. Only when our specifications are correct, will our prices come down.

Most DoD drawings require MIL-D-1000 Category E or F (Identical or Interchangeable Parts) as a specification. It is doubtful that any present set of drawings can meet the test of $\nleq$PT $\leq$ $\nleq$CL or have the ability to reject all noninterchangeable parts, accept all useable parts, and optimize tolerances for function and economy.


SO NICE — Clear tonight, low in mid-50s. Sunny tomorrow, high near 80. Today's low, 53 at 4:30 a.m. Today's high, 78 at 2:45 p.m. Details: Page B-4.

The Evening Star

Stocks—Sports
New York Stock Close: C-7
Prices Today: Mixed
Late Race Results

120th Year No. 154. WASHINGTON, D. C., FRIDAY, JUNE 2, 1972 10 Cents

Prices Higher, Jobless Rate Holds

BIOGRAPHIC SKETCH OF THOMAS BERILLA

Thomas Berilla is a Mechanical Engineer for the Department of Defense and a graduate of the University of Pittsburgh, 1950.

Since 1940, his vocational and professional experience has been in Quality Control and Manufacturing Engineering for US Steel; Product Designer for Automatic Assembly Machines for US Industries and the Syntron Company; Producibility and Value Engineer for Litton Systems and the Value Engineering Company.

He is: Past President of the National Capital Chapter of the Society of American Value Engineers.

Member of: ECSG Inc., SME and Technical Speakers Bureau.

Past Member of: Toastmasters International, JAYCEES, ASME.

As a Mechanical Engineer for the DoD, he reviews for acceptance the adequacy and producibility of mechanical designs on a wide variety of electrical equipments developed by many government contractors.

C. J. CONCEPT FOR ADVANCED AIRCRAFT WIRING

By Dr. Jack Redslob
AMP Inc.

INTRODUCTORY SUMMARY

This paper describes the hardware developed by AMP Incorporated for facilitating the use of flexible flat conductor cable in commercial air transports. (We shall abbreviate flexible flat conductor cable as F.F.C.C.) Included in this family of hardware are universal interconnection boxes, ARINC connectors for use with F.F.C.C. and cable connectors that can be used to connect F.F.C.C. to F.F.C.C. or to round wire.

At least one end of every Cable is terminated in a Connector which plugs into a Junction box. The Junction box provides an interconnection capability between any Conductor in those Cables and Connectors and any or all other Conductors terminated in that Junction box. For these reasons, and the fact that available time was spent on product design instead of coining memorable acronyms, we shall refer to the heart of the system as a C.J. box.

The system was designed with an eye on the necessity for evolutionary transition from the current round wire harnessing to the use of F.F.C.C. harnesses. It was also assumed that ATR racking would continue to be used in new equipment and the C.J. system was designed to be compatible.

The results that can be achieved through proper application of F.F.C.C. wiring and C.J. box systems are simplified and automated fabrication and documentation, and modular assembly and installation of the harnesses. Maintenance and repair, as well as modifications can be accomplished more systematically because the modular concept of the ATR equipment and racking is extended to the interconnecting wiring system.

GENERAL

The advantages of flat wiring have been studied and well documented by NASA, military contractors and major commercial aircraft builders. There is quite a list of publications available, but probably the most comprehensive summary is a MIL handbook which has been circulated for coordination and is currently awaiting printing. Most companies have copies as a result of the coordination activity.

These reports and documents contain large volumes of information that may not be of specific interest in the air transport industry since the paramount interest to NASA and the military was the saving of weight and space. However, the information to substantiate performance, reliability, versatility and applicability to all types of equipment is included and available if one but takes the time to dig for it.

The technical considerations that have precluded widespread use of F.F.C.C. in air transports have been the lack of an automated, economical and reliable means of terminating F.F.C.C. and hardware designed specifically for use in air transports.

This paper describes techniques and hardware to provide the following advantages.

1. Simplification and automation of the fabrication and documentation of harness assemblies through the use of automatic F.F.C.C. terminating equipment, computer controlled machines for the interconnection wiring and computer printouts of the wiring as it actually exists.
2. Modular assembly and installation of harnesses because cables can be prefabricated and tested by automated or computer controlled test equipment prior to, and subsequent to, installation in the aircraft.
3. Simplified modifications since all wiring changes are accomplished by changes to interconnecting panels that may be removed from the C.J. boxes.
4. Easier and simpler maintenance and repair since cables, complete with connectors can be replaced as a modular component.

These advantages should become more apparent as we discuss briefly the F.F.C.C. termination system developed by AMP Incorporated, the C.J. box and associated connectors and adaptors to provide F.F.C.C. compatibility.

AMP'S PRESSURE CRIMP TERMINATION FOR F.F.C.C.

Crimp Barrel

Figure 1 shows the pressure crimp barrel designed for terminating flexible flat conductors. The barrel is formed into the shape of an open "U" with the legs of the "U" swaged sharp enough to pierce cable insulations such as the self-extinguishing polyesters, FEP Teflon or polyimide insulations such as Dupont's Kapton.

Two lateral lances are punched up from the bight of the "U". They are supported during crimping by base material which has been extruded back under the lance. These lances are short, stiff, cantilever springs and will maintain pressure on the conductor if there is any tendency for the crimp to relax subsequent to the crimping operation.

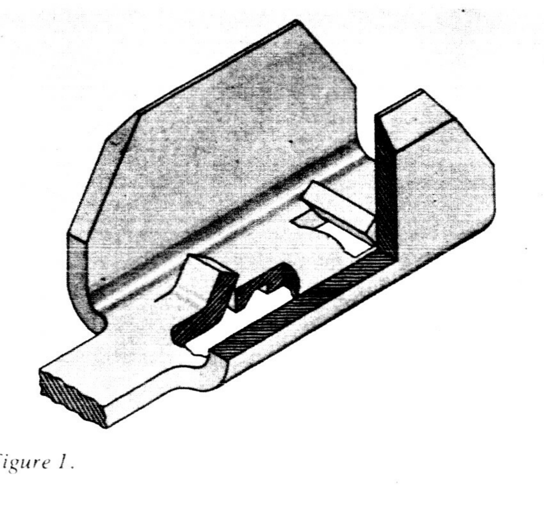


Figure 1.

During crimping, the legs are driven through the insulation astride or through a conductor. When the legs engage the crimper, they are curled in 180° to again pierce the insulation. The lateral lances cut through the insulation from the bottom. At the four points where the legs and lances cross, the insulation is displaced so that there are four metal-to-metal pressure joints. The edges of the conductor also contact the sides of the crimp barrel. The sectional drawing, Figure 2, shows this in detail.

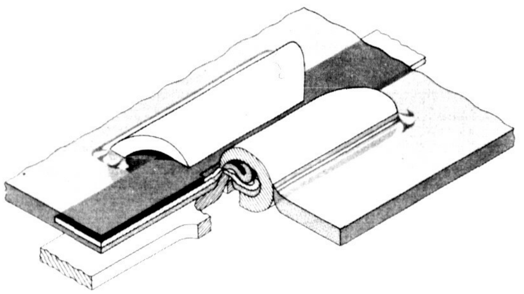


Figure 2.

All plastic has been displaced from the pressure joints as shown in the microphotograph, Figure 3. The conductor shown in this illustration is plated to more specifically define the interface but is not necessary for good performance.

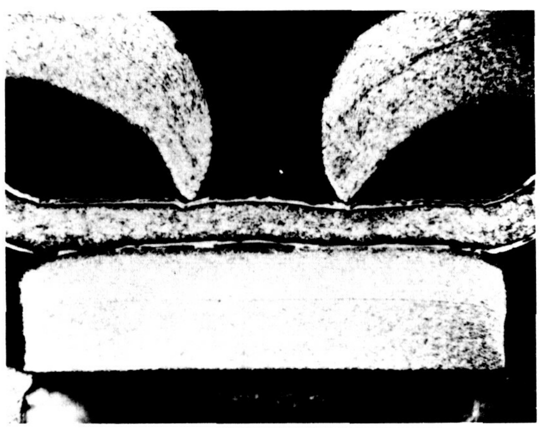


Figure 3.

The internal volume of the crimped barrel is sufficient to accommodate the total included volume of cable conductor and insulation having a total thickness of .015 inch or less. No destructive extrusion of the plastic occurs during crimping.

A large family of contact styles with this crimp barrel have been tooled and printed information is available. A concerted effort has been made to maintain uniformity of critical dimensions so that the various contacts can be crimped in the standard terminating tools.

Terminating Equipment

Figure 4 shows a bench-mounted, motor-driven, reel-fed applicator for production use. A cable is clamped in the carriage and the crimping sequence started by the operator. Contacts are then crimped to the conductors at the rate of 120 per minute.

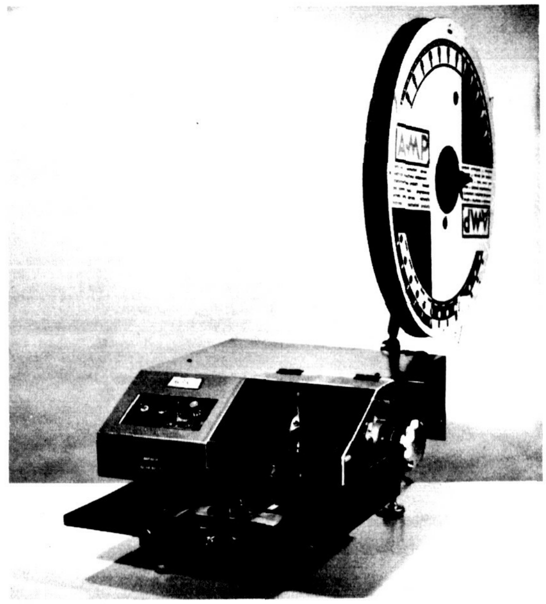


Figure 4.

Simple adjustments make it possible to terminate cables of various widths ranging from 6 to 33 conductors at .100 inch centers.

A hand tool, Figure 5, is available for maintenance and repair and small production usage. Contacts are loose piece and hand fed and the cable carriage is manually indexed. When used for splicing, cables up to 3½ inches in width can be accommodated by simply curling them in the throat of the tool.

Figure 5.

Special Cables

Although the principal mode of interconnection is standard F.F.C.C., circuit requirements may dictate special handling of some circuits. Higher degrees of circuit criticality can be handled by special organization of conduc-

tors within a standard F.F.C.C., or with several types of special cables which have been designed specifically to be compatible with the pressure crimp termination. Cables may have foil interleaved to provide shielding or cables can be made up with shielding material laminated to one or both sides.

Simulated twisted pairs in flat configuration are available as shown in Figure 6. Impedance matched flat conductor transmission cables as shown in Figure 7 are also available.

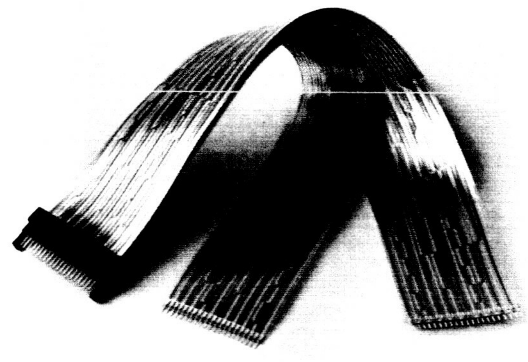


Figure 6.

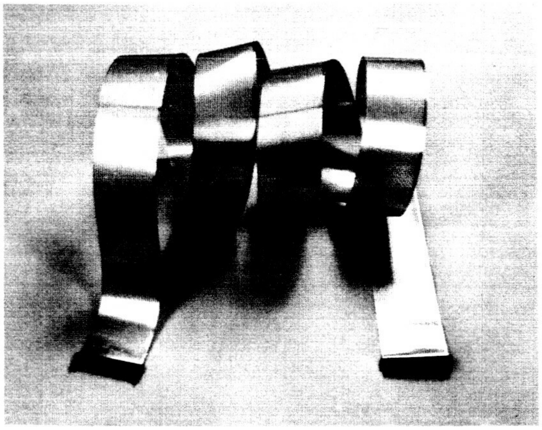


Figure 7.

There is no doubt that coaxial cables will continue to be required for many circuits and it is proposed that these be handled separately from the F.F.C.C. and C.J. system.

Repair Capability

Although complete replacement of a damaged cable and connector assembly is normally recommended, all connectors are designed so that the terminated contacts can be removed from the connector housing, serviced and reinserted. In addition, every contact crimpable to F.F.C.C. has a counterpart which can be crimped to round wire and which will fit in the same connector cavity. This enables an emergency repair of a damaged conductor by extracting the contacts terminating that conductor, and replacing them with a round wire terminated with the appropriate contacts.

SYSTEM COMPONENTS

The C.J.

Most simply, the connector junction box is a means of connecting any wiring point to any other wiring point in an aircraft. C.J. units offer advantages over conventional wiring methods at any level of usage on the airplane. They can be used singly to interconnect units in a functional sub-system, they can be used in combinations to

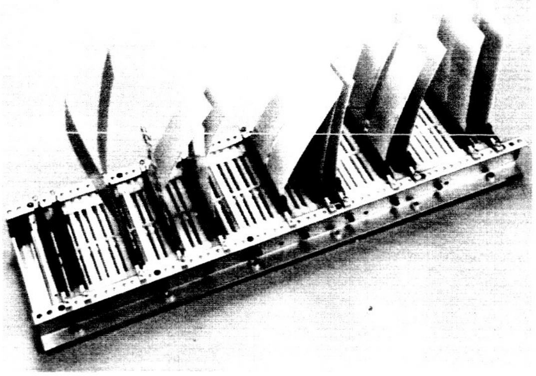


Figure 8.

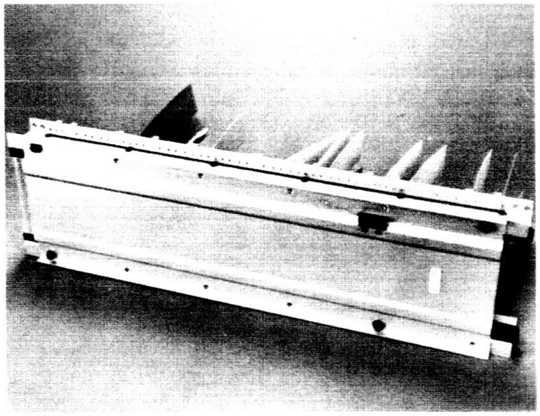


Figure 9.

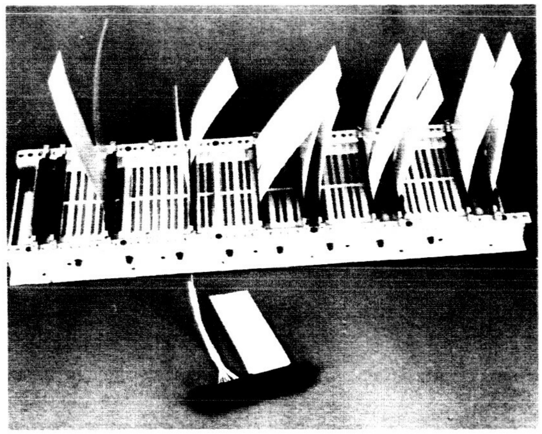


Figure 10.

wire an entire ATR racking system, or they can be distributed throughout the airframe to act as principal junctioning points.

The C.J. box, as shown in Figures 8 through 10, consists of a structural framework carrying modules which accept connectors, an interconnecting panel, and related mechanical hardware. The framework has a ladder configuration. Between the "rungs" of this ladder are receptacle modules into which connectors are plugged. Latches for the connectors are carried by the side rails.

A linear cam is also carried inside of the frame on the side opposite the connectors. See Figures 11 and 12. This cam provides engagement means for the interconnecting panel.

The interconnecting panel is the functional heart of the C.J. unit. This is a structural aluminum part which carries feed-through pins that mate directly with the previously mentioned connectors and also provide termination posts for TERMI-POINT* clips. See Figures 11 and 12.

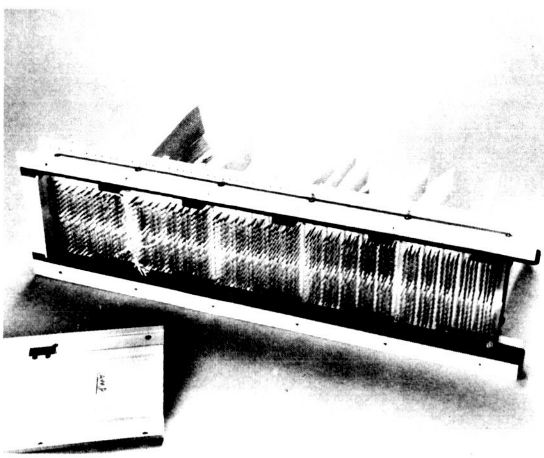


Figure 11.

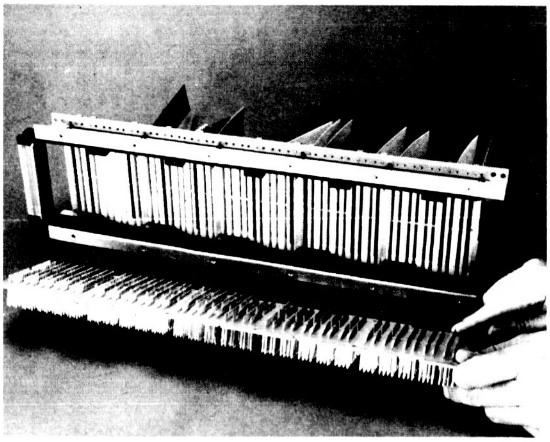


Figure 12.

*Trademark of AMP Incorporated

The unit assembly is completed by the addition of an access cover which protects the posts and wiring.

It should be stressed that C.J. panels provide any point to any other point interconnection capability on an entirely random basis. Furthermore, the TERMI-POINT clip method of wiring can be completely automated from wire list to final checkout. In addition, this panel is completely maintainable on the flight line with hand tools or, at the user's option, may be removed from the C.J. box for service or replacement.

The linear cam for loading and ejecting the wiring panel permits the panel to be plugged into the frame either before or after the connectors are plugged into their receptacle modules. Thus, it is possible to easily change wiring schemes within an aircraft by replacing prewired panels. Similarly, cable assemblies can be replaced without concern about changes in the point-to-point scheme.

C.J. equipment can be made in either sealed or unsealed versions. AMP Incorporated has built prototypes of both configurations. The unsealed C.J. box is a minimum weight unit having near optimum packaging density. It is shown in Figures 8 through 12.

The sealed C.J. uses silicon rubber seals and gaskets to effect an environmental enclosure. Figure 13 shows a portion of a sealed C.J. box with two F.F.C.C. connectors in place. Obviously, a compromise in packaging efficiency must be made in the design of sealed units. The user's requirements will determine whether sealed or unsealed C.J. systems are more apropos.

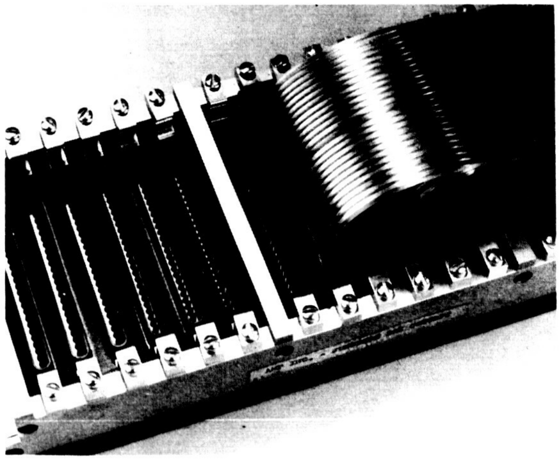


Figure 13.

TERMI-POINT Products

The wired panels housed in C.J. boxes electrically connect any point to any other point in the C.J. system. This wiring is completely automatable. AMP programming techniques and TERMI-POINT numerically controlled machines make it possible to begin with basic "to-from" wire lists and wind up with finished wiring panels. These panels may also be automatically inspected and completely documented via computer printout wire listings.

TERMI-POINT products provide a unique wiring system. Stranded wires up to AWG 24 can be handled completely automatically and wires up to AWG 22 can be applied by hand.

Electrically, this technique works by using spring clips to hold wires in intimate contact with posts. The wire-clip combination makes it possible to conveniently service these wiring panels. Clips can be removed at any wiring level, and wires reterminated. Furthermore, the clips and wires may be slipped downward on a post to make room for additions and modifications to the point-to-point scheme.

TERMI-POINT products have been proven to be reliable and documentation is available from AMP Incorporated. Currently, they are flying inside "black boxes" on both civil and military aircraft.

Cable Connectors

In-line connections along the length of cable runs are often necessary for "construction breaks" or to facilitate service and maintenance of aircraft. Connectors for this purpose are available for either sealed or unsealed systems. The sealed version is shown in Figure 14 and an unsealed type is shown in Figure 15.

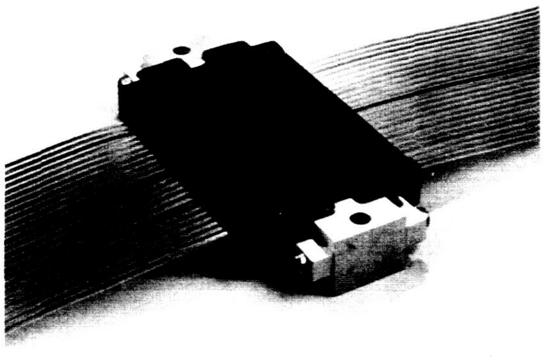


Figure 14

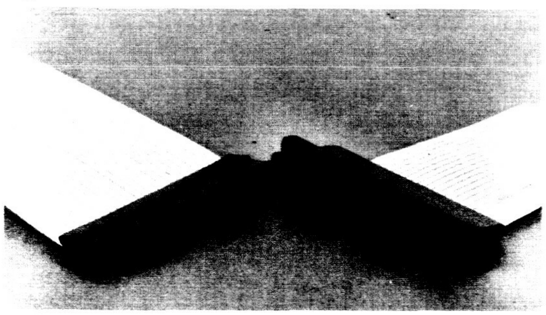


Figure 15.

In practice, the female half of a cable connector of this type is the same as the connector which enters C.J. boxes. The male half is a separately designed piece which has a pin protecting shroud. Either half will accommodate round wires as well as F.F.C.C. and both have contacts which use the F.F.C.C. termination methods described above.

ARINC Connectors and F.F.C.C.

In order to maintain the ATR rack interface, it becomes necessary to terminate F.F.C.C. in the ARINC receptacles. In the case of connector shells meeting MIL-C-81659 and ARINC 404, with contact spacings of .100 inch, this requires only a contact crimpable to F.F.C.C. and an appropriate insert assembly. These parts are being tooled and Figure 16 shows an assembly.

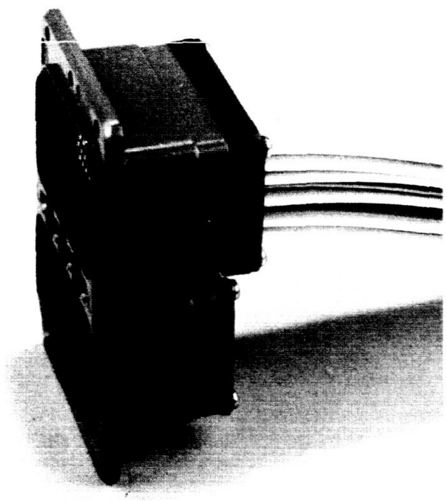
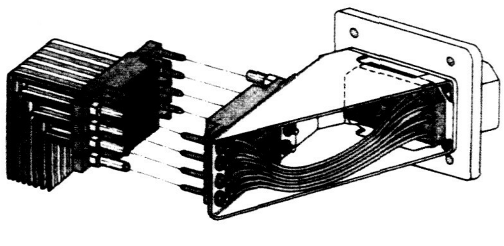


Figure 16.

For the connector insert arrangements at contact spacings other than .100 inch, adaptation to the uniform spacing of F.F.C.C. can be accomplished as shown in Figure 17. The receptacle half of an F.F.C.C. to round wire connector is mounted on a bracket which is fastened to the connector shell and prewired in a uniform pattern so that the assembly can be purchased, stocked, installed or replaced as one part number.



ARINC CONNECTOR WITH FLAT CABLE ADAPTOR

Figure 17.

APPLICATIONS

Functional Sub-systems

The C.J. box offers a most facile means of interconnecting between units that form functional sub-systems. As an example, the various "black box" equipments which handle attitude control on an aircraft may be racked together and interconnected via a C.J. unit. Electrical access to the whole sub-system would be through C.J. connectors. F.F.C.C. would connect individual "black boxes" to the C.J. box and all point-to-point wiring would be made on the wiring panel inside the C.J. box.

ATR Equipment Racks

The application to actual aircraft has been studied most intensively for wiring the ATR equipment rack in one of the air transports currently in production. The following illustrations resulted from the assignment to demonstrate that the round wire harnesses could be replaced with F.F.C.C. without changing the ATR equipment interface or the interface between the equipment bay and the airframe wiring.

Figure 18 shows a schematic of the cabling runs within the rack while Figure 19 shows an isometric view, to scale, of approximately one-half of the rack.

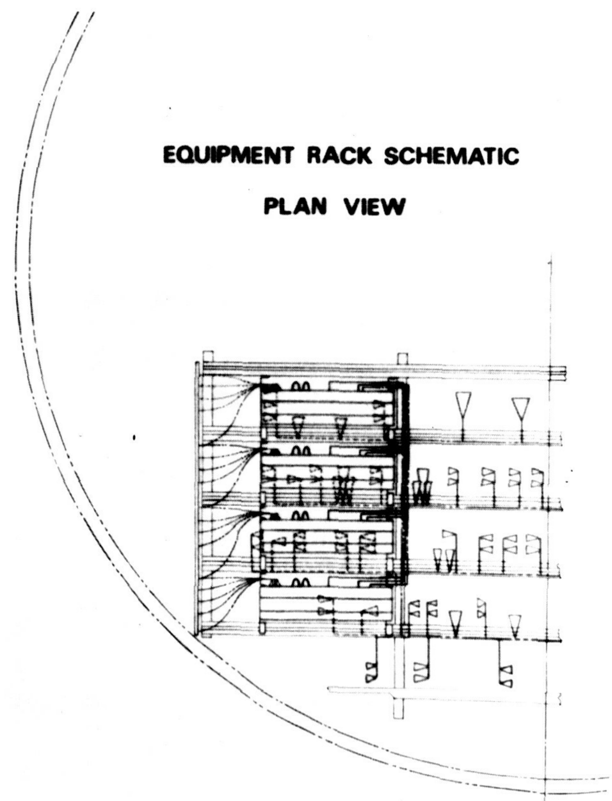
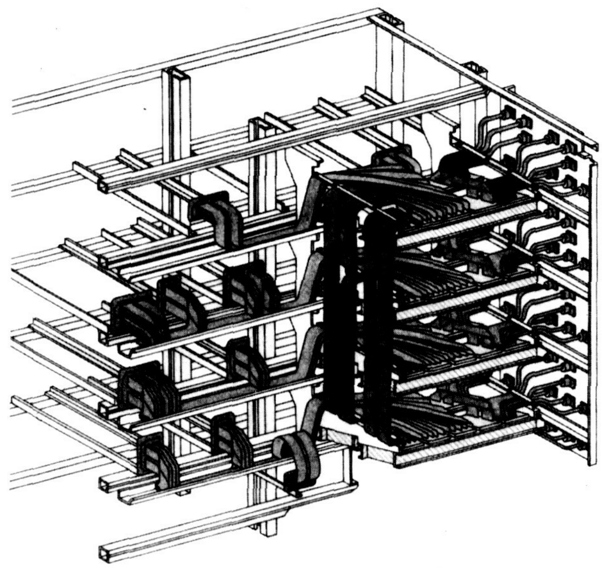


Figure 18.

C.J. boxes were located near each end of each shelf. Interwiring of all equipment on one shelf was accomplished by F.F.C.C. routed from ARINC connectors to C.J. boxes. Figures 18 and 19 both show the horizontal routing of these cables.



EQUIPMENT RACK

Figure 19.

All shelf to shelf wiring was accomplished by routing F.F.C.C. from C.J. box to C.J. box.

The transition from the F.F.C.C. harnesses in the ATR equipment bay to the main airframe wiring was accomplished by running round wire jumper cables from the C.J. boxes to circular connectors mounted in the end panels of the rack. The connectors in the end panels are necessary for the round wire harnessing system now in use but a dramatic decrease in complexity could obviously be accomplished by eliminating them and terminating the cables in the C.J. box.

Airframe Wiring

Evolutionary steps to incorporate F.F.C.C. in increasing portions of the airframe wiring is easier than in the ATR equipment racks.

The most advantageous use is in the long straight runs, and can be accomplished in combination with conventional round wire cables where they are deemed necessary.

C.J. boxes located at strategic locations can provide both the transition from F.F.C.C. to round wire as well as provide the any wire to any other wire interconnection capability.

ADVANCED WIRING TECHNIQUE AND HARDWARE APPLICATION – AIRPLANE AND SPACE VEHICLE

By H. L. Ernst
The Boeing Company

ADVANCED WIRING TECHNIQUE AND HARDWARE APPLICATION
AIRPLANE AND SPACE VEHICLE

C. D. EICHMAN
H. L. ERNST
THE BOEING COMPANY

This presentation will develop an Advanced Wiring System achieving the safety/reliability required for present and future airplane and space vehicle applications. Also, present wiring installation techniques and hardware will be analyzed to establish existing problem areas. An advanced wiring system employing matrix interconnecting unit, plug to plug trunk bundles (FCC or ribbon cable) will be outlined and an installation study presented. A planned program to develop, lab test and flight test key features of these techniques and hardware as a part of the SST Technology follow-on activities will be detailed.

INTRODUCTION

Military and commercial airplanes and space vehicles have experienced significant growth in the application of electrically operated equipment and components. With this trend, the requirements for power and signal circuit wiring has increased many fold. As a result, vehicle wiring weight, cost and complexity have become increasingly greater with each new program. Efforts have been made to reduce size and weight of vehicle wiring by use of smaller and smaller wire sizes, lower density insulation materials, lighter weight conductor materials, and thinner wall insulation constructions. In spite of these approaches, the total vehicle wiring weight trend is still increasing from design to design. (Figures 1 thru 4).

In addition to the penalties of size and weight, vehicle wiring has accounted for considerable manufacturing costs and maintenance costs. Past and present vehicle wiring system designs have resulted in these cost factors due to inability to cope with system circuit modifications in manufacturing and operations and repair facilities.

An example of past designs which typify these problems is included (Figure 5). Attempts have been made by each program to overcome these penalties in the wiring system. Generally these efforts have been directed towards application of new materials and parts on an isolated basis without an "overall systems" effort. This usually is accounted for due to the following rationale:

- Wiring Research and Development activity is not competitive with the more sophisticated systems such as Flight Controls, Navigation, Advanced Displays, etc.,
- High start-up costs and relative low unit costs for most materials and parts within the wiring system,
- Complexity of the system for the total vehicle insofar as the number of wire segments and terminations, and
- Requirement for the basic wiring system to incorporate a service life equivalent to that of the vehicle structure.

Wire Length per Airplane

FIGURE 1

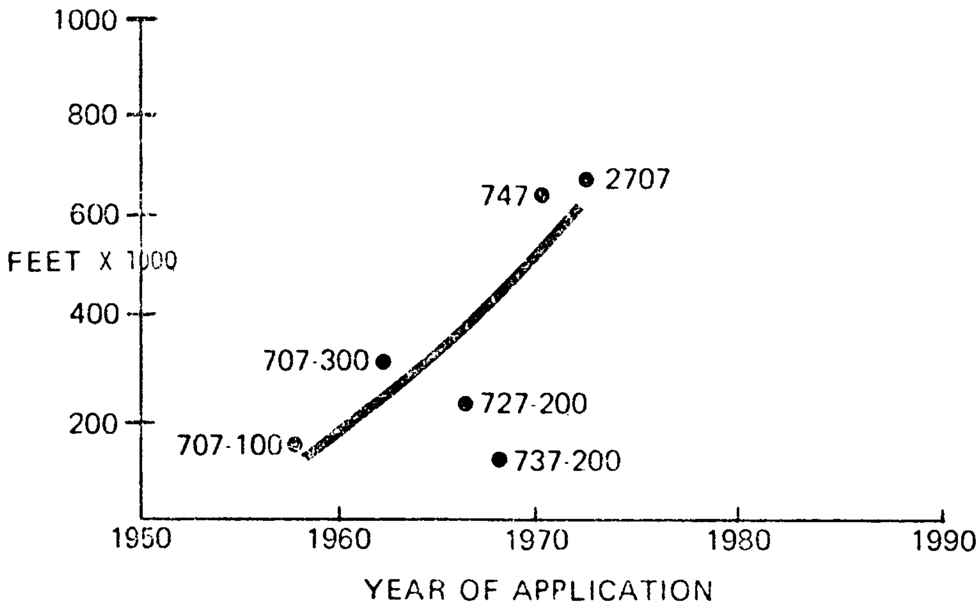


FIGURE 2

Weight (LB 1000ft) Comparative Values Only

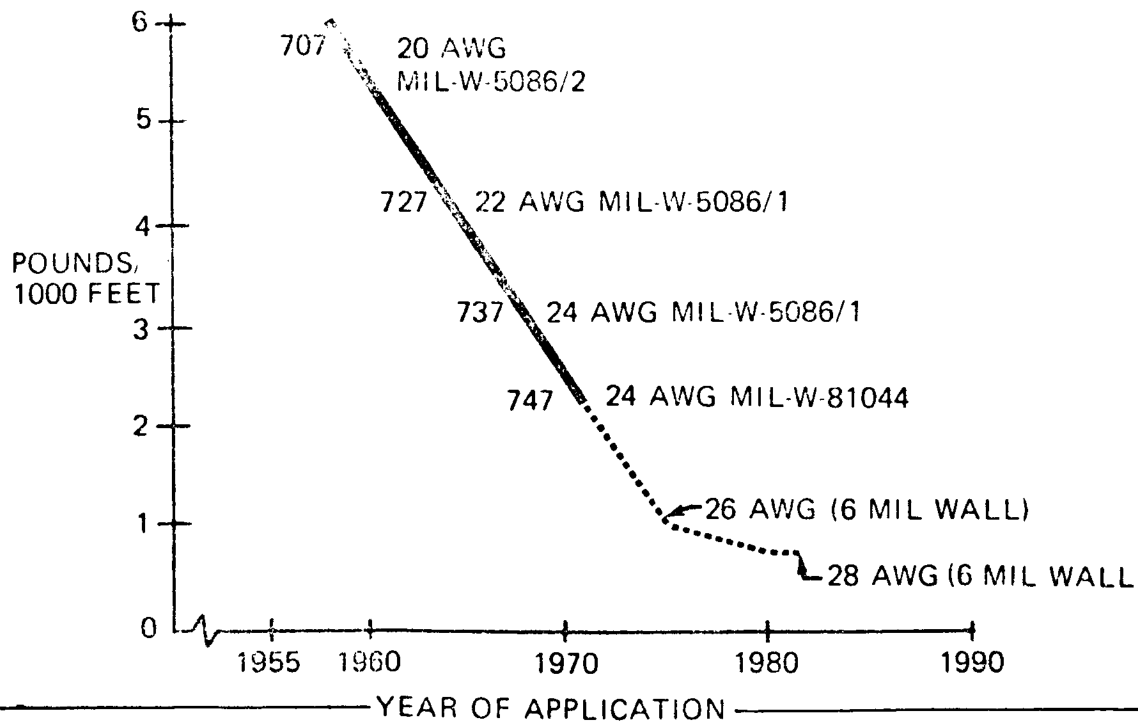


FIGURE 3

Wire Weight per Airplane

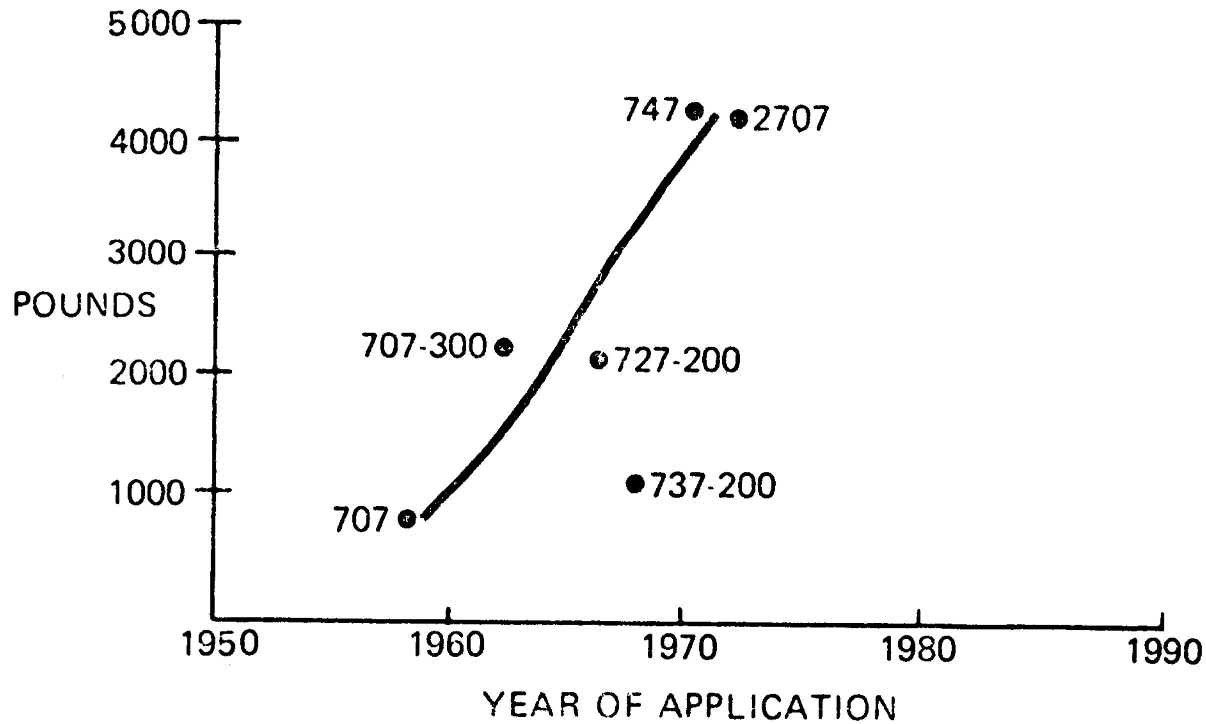
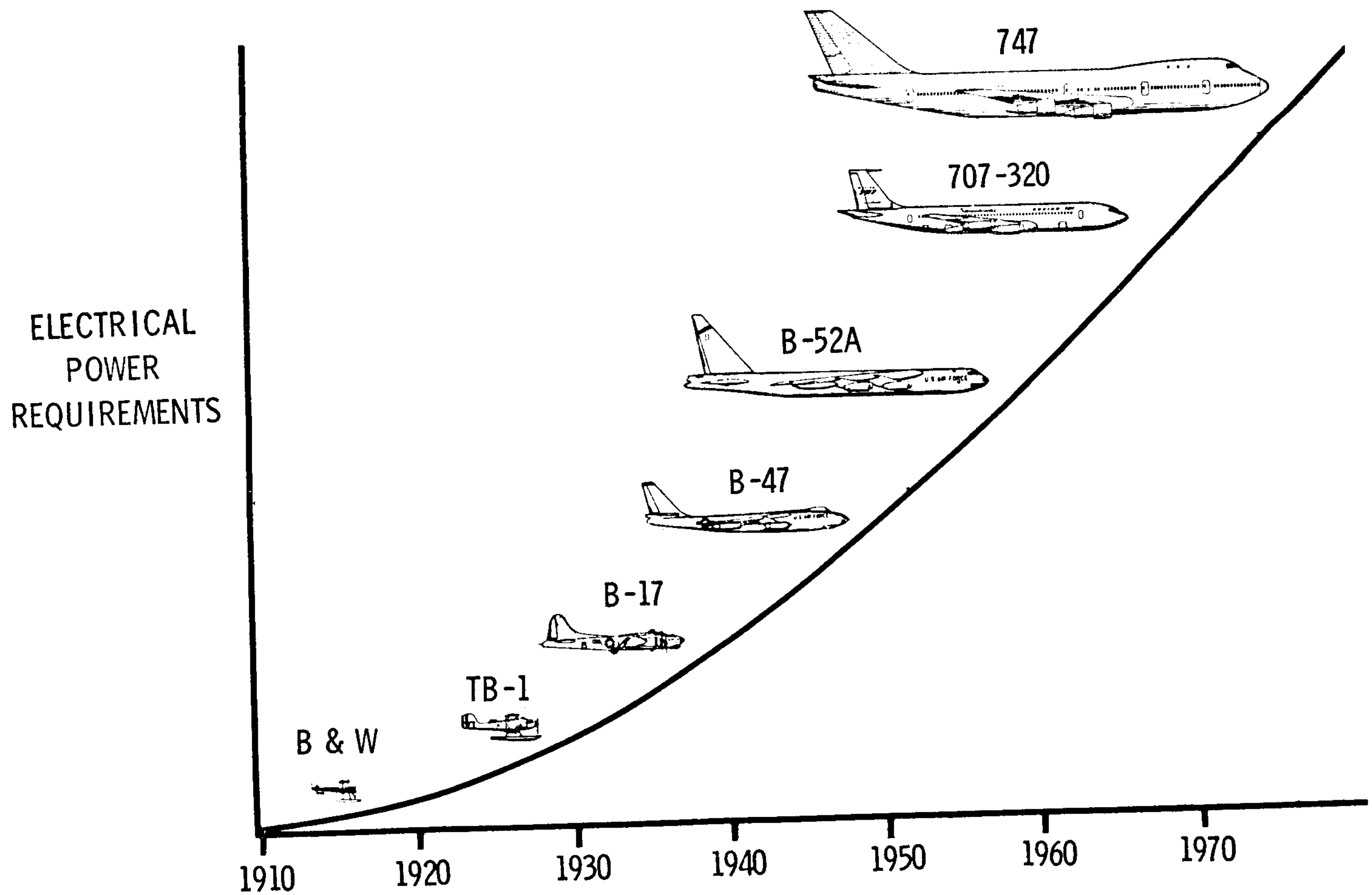


FIGURE 4

ELECTRICAL POWER GROWTH



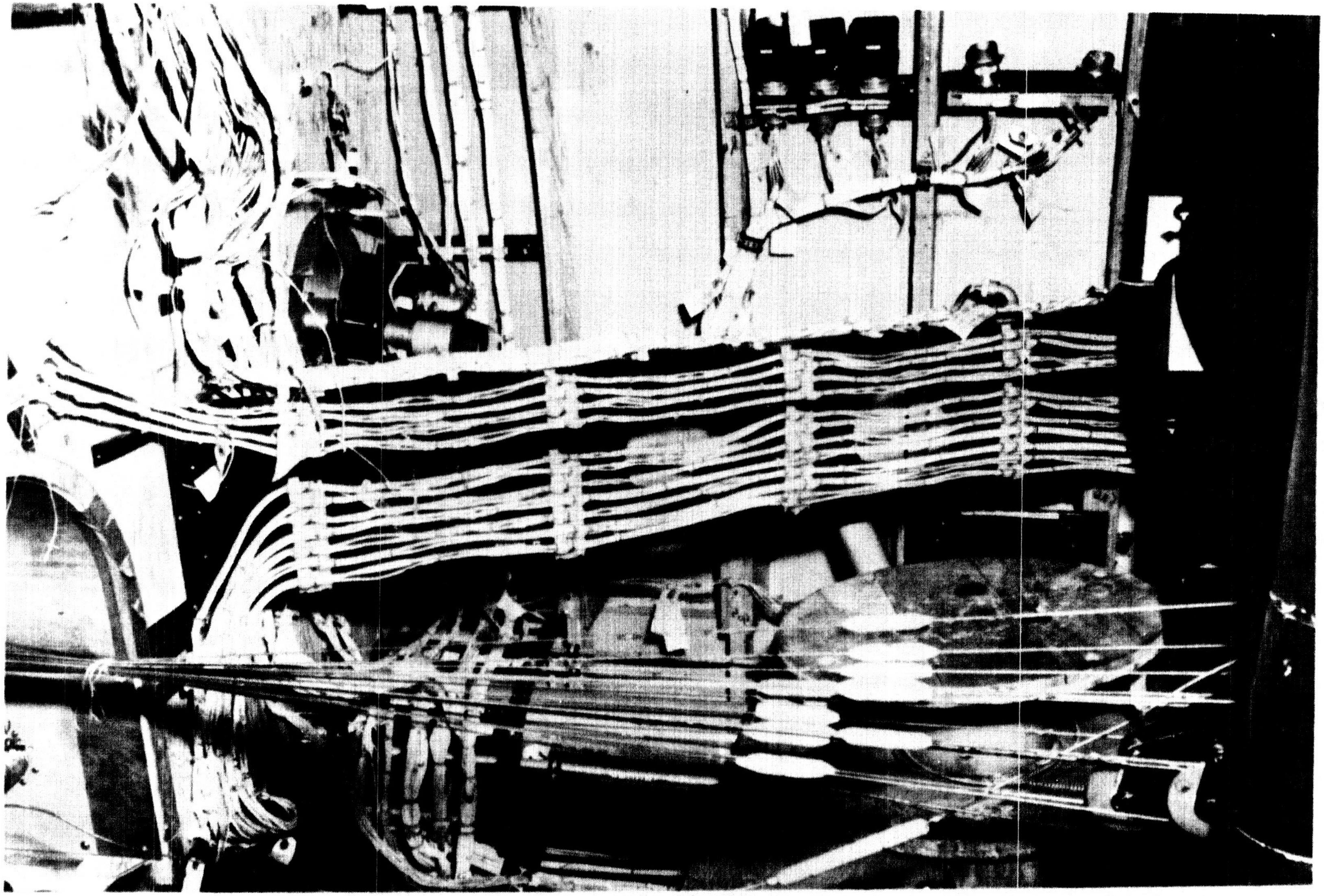


FIGURE 5
TYPICAL WIRING CONGESTION

As a result of the above points, wiring system design evolution in the aerospace industry has exhibited conservative trends to assure design integrity and acceptable service.

BACKGROUND

As an example of increased wiring complexity, the wire bundle count of commercial airplanes has grown from 338 in the Model 707 to 1,004 bundles in the Model 747. The preliminary wire bundle count in one of the current military airplanes being developed is estimated at 1,500 bundles.

Advanced wiring techniques and hardware studies have been initiated by various users from time to time. These hardware studies included new materials, innovative wire (such as Flat Conductor Cable (FCC), ribbon wire, woven cable, etc.), and new connector concepts. As individual parts, most of the available hardware in today's inventory for wiring systems have been around for some time. An example is the Auto-Pilot Integration Center designed for the 707 airplane in the mid 1950's. (Fig. 6 & Fig. 7). Integration concepts have evolved thru various stages from that point taking such form as a "line up" of integration connectors located adjacent to equipment rack, use of terminal junction modules, printed circuit cards with a matrix layout (Sabena Airlines SIMPL System), and a number of other schemes. Use of these concepts in the more complex aircraft presently planned for initial in-service application in the latter half of the 1970's would not provide the flexibility required for a cost effective integration scheme.

The concept of an "Interface-Unit-Wiring" box was initially envisioned during the Boeing SST studies dating to 1965. (Fig. 8 & Fig. 9). These studies have subsequently been evolved to more practical configuration and use of advanced connection hardware and termination parts than were available at that time.

ADVANCED WIRING APPROACH

To achieve a major step in reliable wiring, it is required that an "Overall Systems" approach to wiring be established <u>with priorities</u> during the initial airplane or space vehicle development program. This study and development effort must include special hardware development, new materials as required, and installation studies through the mock-up phase. Some of the key features to be considered are (Fig. 10)

- Matrix Integration units located at the major equipment centers and at the various vehicle transition points (fuselage to wing, fuselage to empennage, pressurized to non-pressurized),
- Plug to Plug "trunk bundles",
- Multiconductor cable configurations (using FCC, ribbon wire, or SGW),
- Other associated components such as connectors, transition breakouts or splices, clamps, etc., to result in the optimum inherent program benefits of the above items, and
- New materials for both insulation and conductor application.

FIGURE 6

Model 707 Autopilot Junction Box

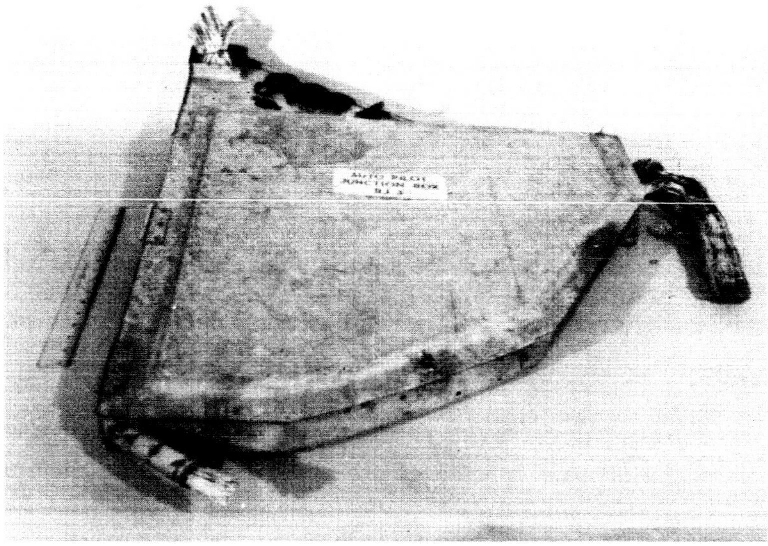


FIGURE 7

"AN" Terminal Strip Wiring Integration Center

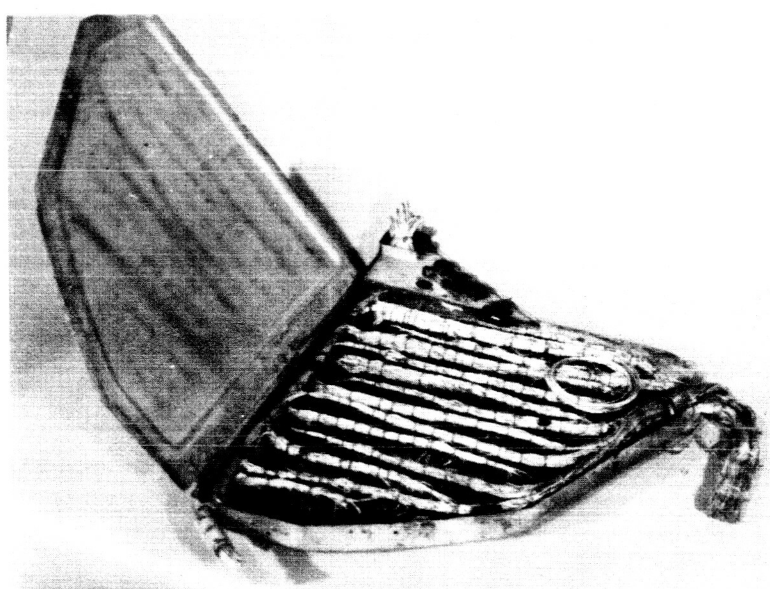


Figure 8

ELECTRONIC INTERFACE UNIT - WIRING

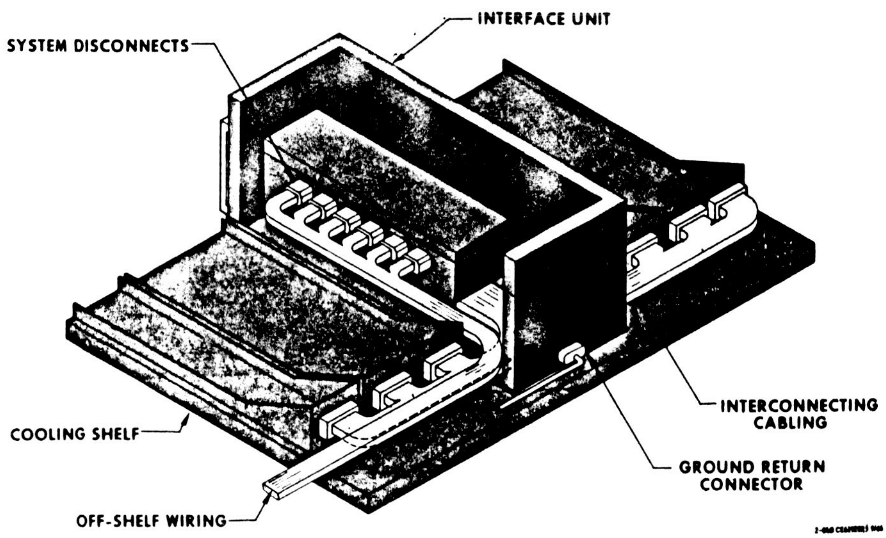


Figure 9

ELECTRONIC INTERFACE UNIT INSTALLATION

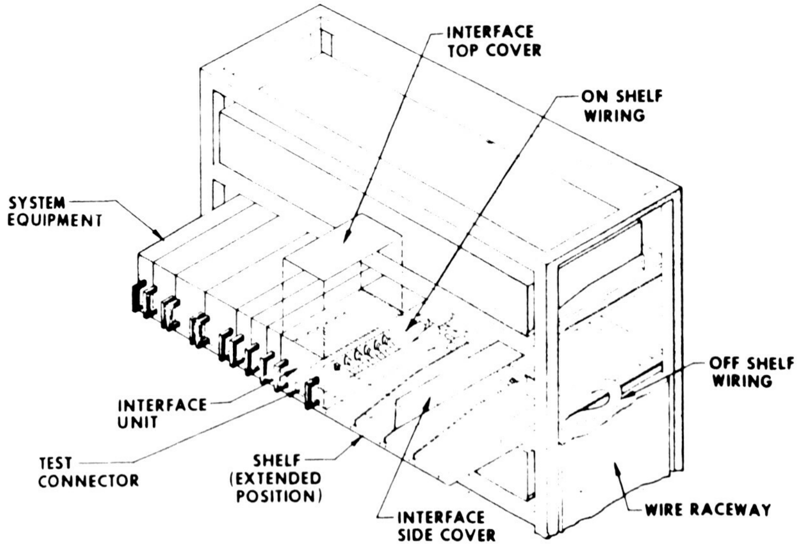
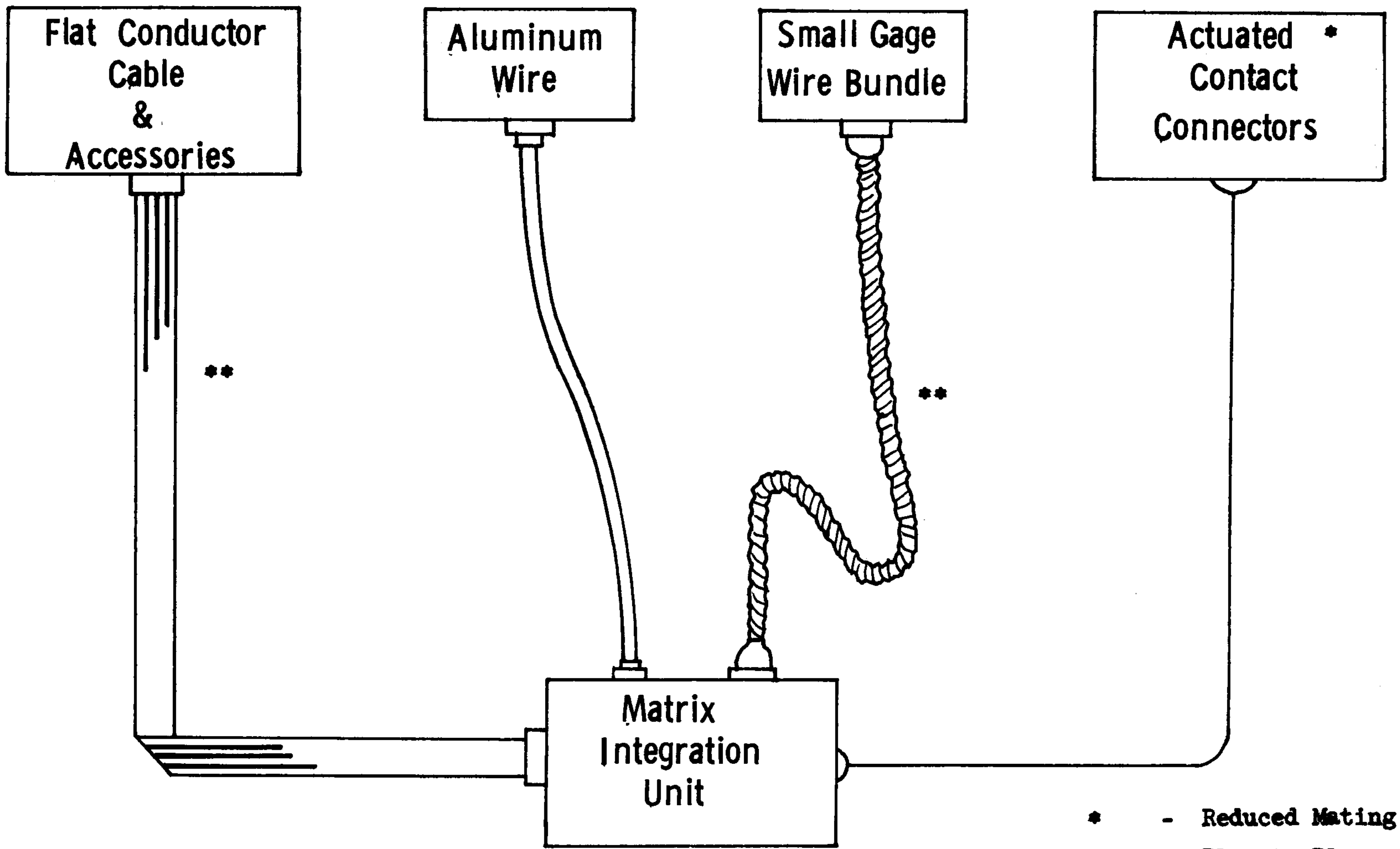


FIGURE 10

ADVANCED WIRING DEVELOPMENT PROGRAM



* - Reduced Mating Forces

** - Plug to Plug "Trunk Bundles"

MATRIX UNIT DEVELOPMENT

Recent studies and test installations of FCC and Matrix Units have been made at Boeing - Seattle. These include a test installation on the 707 Prototype (Model 367-80) airplane consisting of a FCC bundle with a matrix unit on each end, replacement of the standard wiring with FCC in the T-1 raceway of the 727-100 Mock-up (Fig. 11), and use of FCC in both the upper deck passenger entertainment floor wiring (production application) and a test installation in the VHF/SAT communication system in the Model 747 airplane.

With the advent of the SST follow-on Program, one of the ten tasks consisted of both a laboratory and flight test of the Advanced Electronic Display System (ADEDS). This program presented the opportunity to apply both the matrix unit and use of FCC, ribbon cable and braided multi-conductor small gage wire (SGW) bundles. The key development item is the Matrix Unit.

Subsequent to establishing a specification and receiving proposals from the industry, the design submitted by the Burndy Corp. was selected for use on this program. (Figures 12, 13 & 14). An alternate design has also been established to assure program success in the application of a matrix unit in the event of unforeseen schedule slides of the primary program (Figure 15).

The Matrix Unit selected consists of a "Base Unit" and two "Modules". Each module will contain a terminal junction field and one half of an accuated contact connector which mates to the Base Unit. The Base Unit will accommodate input/output connectors for mating with both the shelf wiring and ship's wiring. These connectors then may be selected on a program basis to be compatible with specific wire type and configuration planned for that application. Also, the Base Unit incorporates the receptacle half of the actuated contact connector and the actuating mechanism.

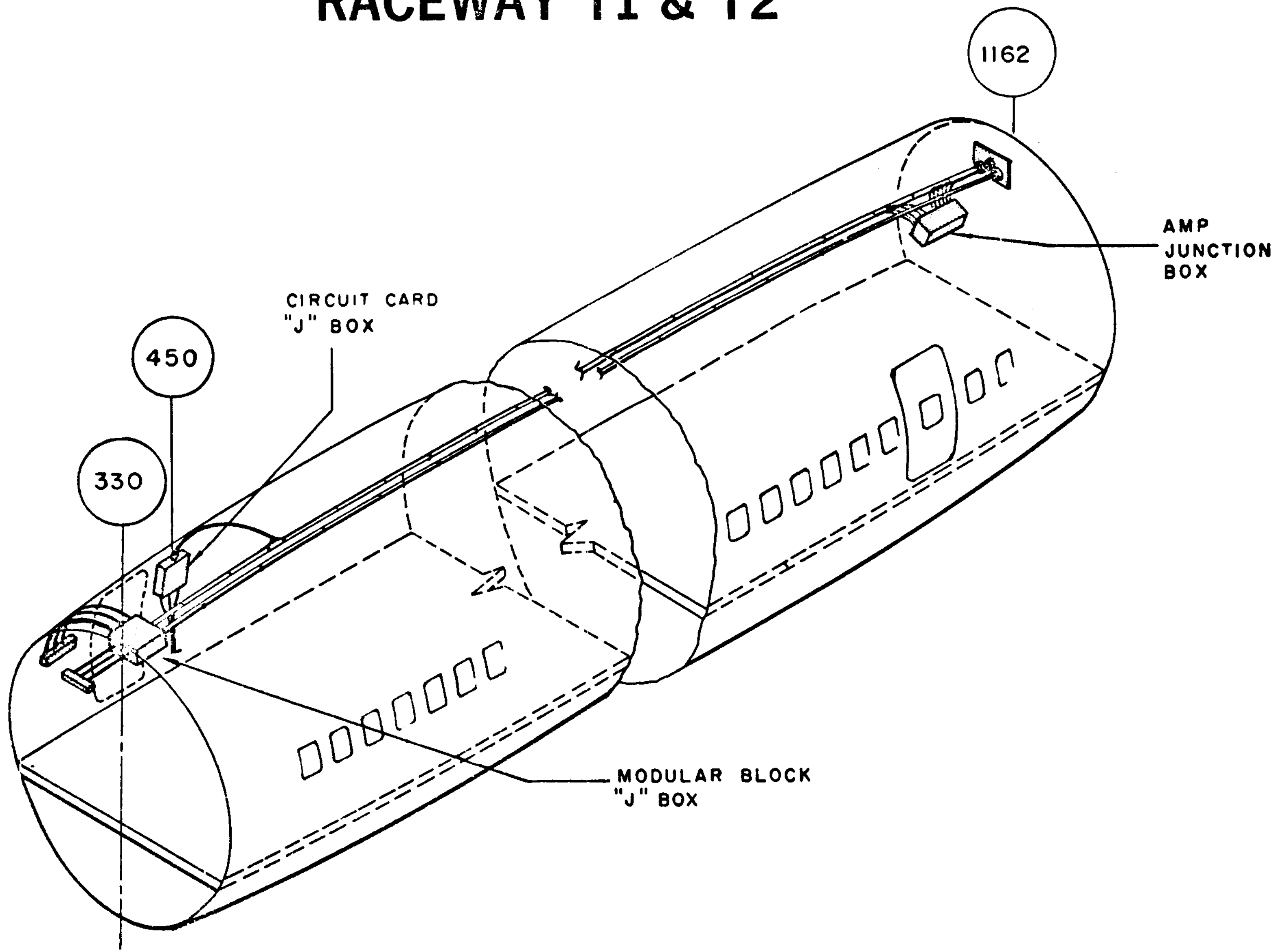
Some of the pertinent factors considered in the design as presently defined are:

- The form factor allows installation at the rear of the equipment shelf in the area where the shelf wiring is traditionally installed.
- The size of the Base Unit was limited to 266 input and 266 output circuits.
- Each module has a matrix field of 552 positions.
- Individual circuit changes within the module may be accomplished in place and any module may be removed and replaced without disturbing the Base Unit or the adjacent Module.
- The matrix field within each module consists of a two by two dedicated arrangement (two field positions for each input circuit and two field positions for each output circuit) and 20 spare positions which may be used for additional integration of the input/output circuits, handling of shielded circuits, equipment and system grounds.

This Matrix Unit is scheduled for qualified delivery in the first quarter of 1973 with application to test pallets by second quarter of 1973 and subsequent ADEDS laboratory and flight tests in the latter part of 1973.

FIGURE II

727 CABIN OVERHEAD RACEWAY T1 & T2



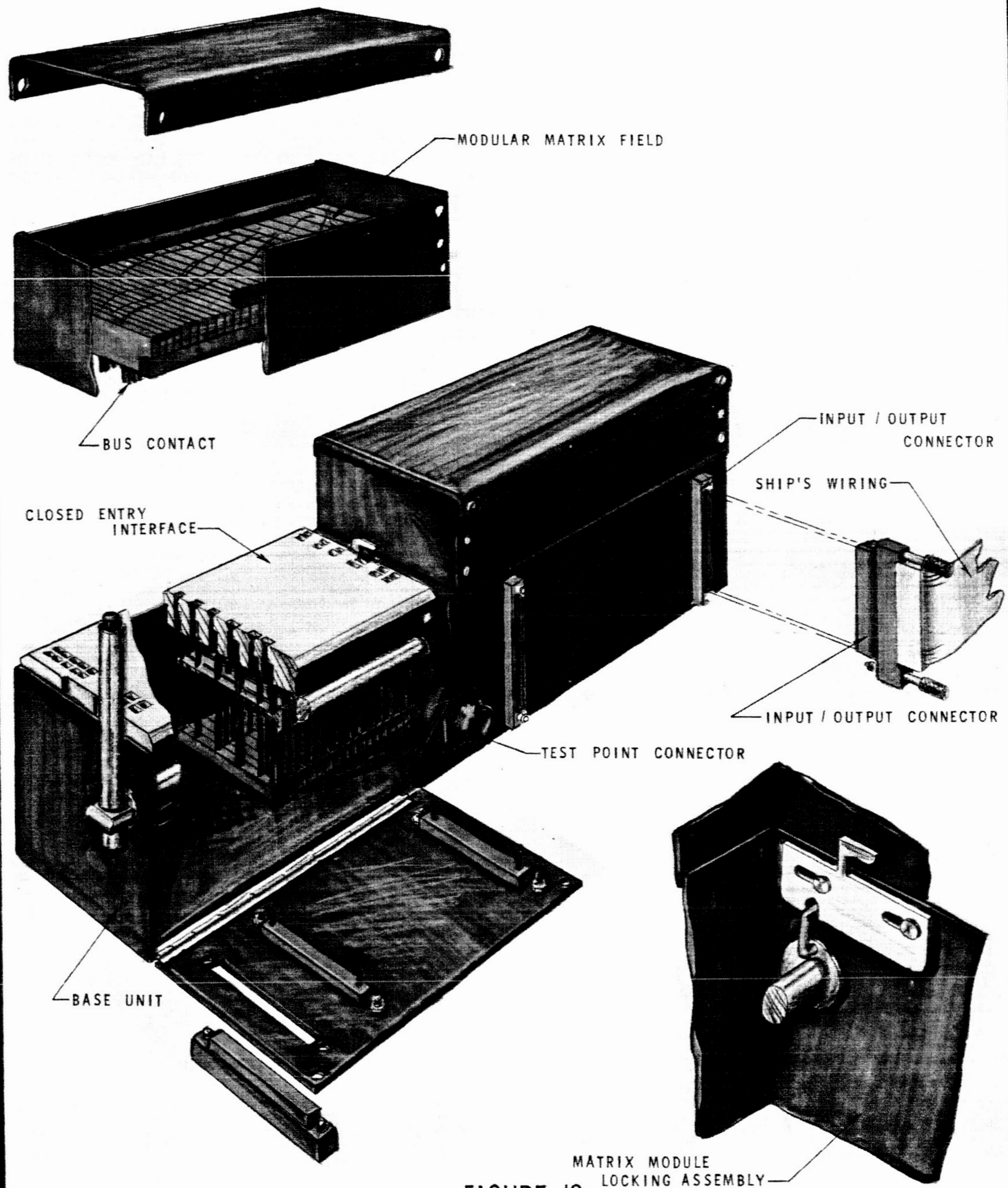


FIGURE 12
SIAM

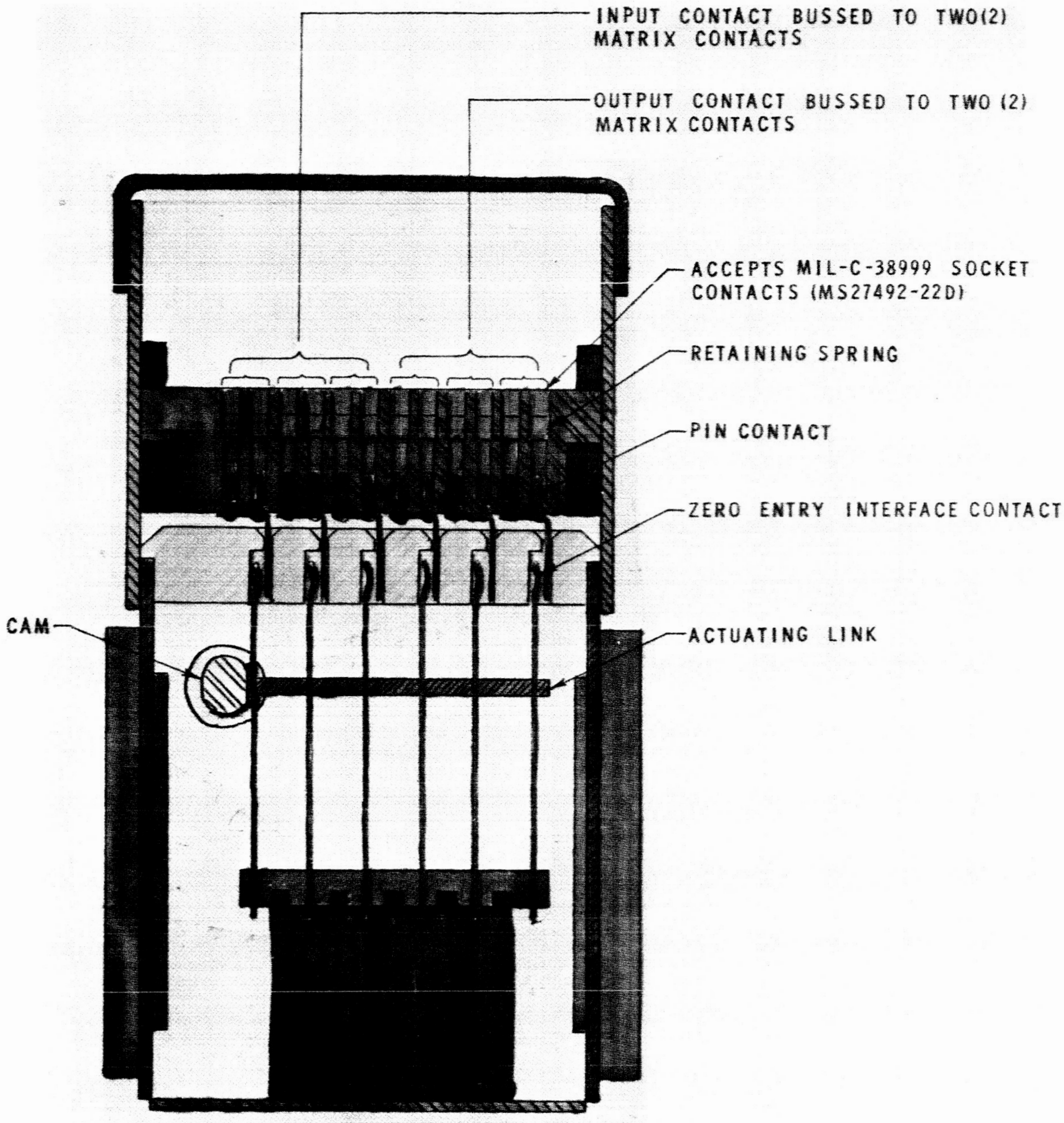


FIGURE 13
SIAM CROSS SECTION

FIGURE 14
Burndy Matrix Unit

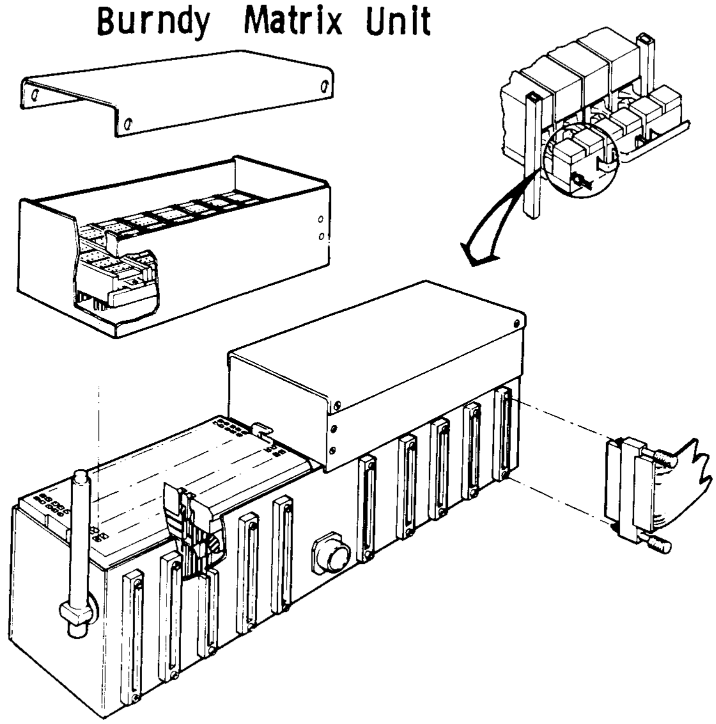
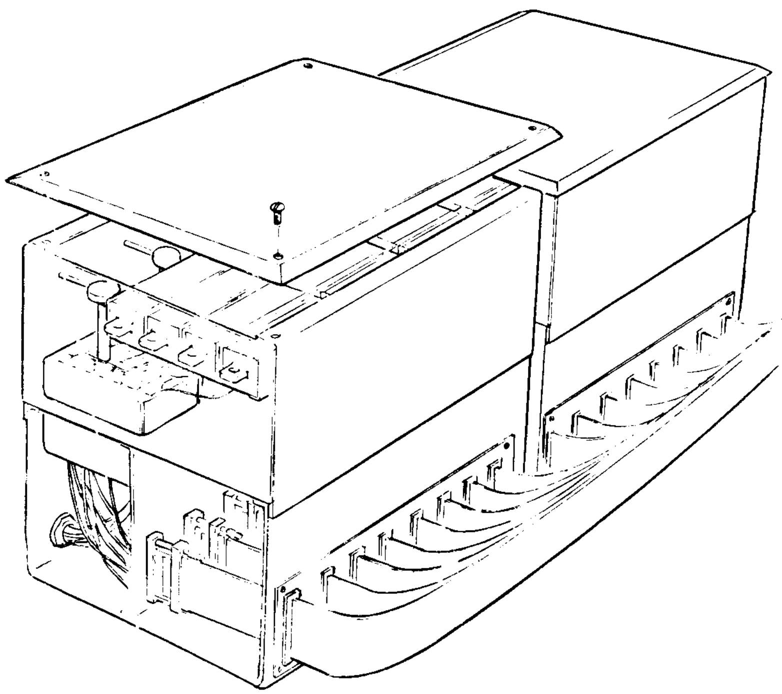


FIGURE 15
Boeing Designed Matrix Unit



MATRIX UNIT DEVELOPMENT (continued)

The ADEDS Program presents the opportunity for development and application of Matrix Units, FCC, SGW in a total advanced wiring system. The ADEDS Program incorporates advanced displays (EADI, PND, and MFD), Inertial Navigation System, and Digital Flight Control System. Therefore, this installation will prove the use of these wiring techniques during laboratory tests and flight tests on a Model 737 airplane in the more sensitive avionic systems incorporating low-level analogue and digital signals.

MATRIX UNIT PRODUCTION APPLICATION

Initial studies of an airplane development program limited to the electrical/electronic equipment bay has determined that the following matrix unit quantities would be required:

System	ATA Chapter	Quantity of MU's
Air Conditioning	21	2
Pneumatic	36	
Auto Flight	22	2
Communications (Flight Crew)	23	2
Electrical Power	24	
APU	49	N/A
Fuel System	29	1
Flight Control	27	1
Hydraulics	29	1
Landing Gear	32	1
Equipment & Furn	25	
Ice & Rain	30	1
Water & Waste	38	
Lights	33	1
Oxygen	35	N/A
Doors	52	N/A
Fire Protection	26	
Engine Indicating	77	1
Oil (Engine)	79	
Navigation (Flight (Essential)	34	2
Ignition	74	N/A
Starting	80	N/A
	Total per Airplane	15

TABLE 1 MATRIX UNIT USAGE STUDY

Also, other typical installation areas requiring one or more Matrix Units are the Pilots/Co-Pilots Instrument Panels, Center Instrument Panel, Overhead Panel, Fuselage to Wing Transitions, and Fuselage to Empennage Transition.

MATRIX UNIT PRODUCTION APPLICATION (CONTINUED)

Use of the Matrix Unit would allow standard connections of input/output wiring to the base unit in production or overhaul and flight line installation of the modules with the matrix field complete. Also, modified modules could be developed to tie into an automatic wiring tester and checkout ship's wiring as installed.

The Matrix Unit and the associated module have been presented with a matrix field consisting of Terminal Junction modules. This approach provides circuit by circuit change capability in the field with a minimum of new tooling. However, it is limited to semi-automatic tooling in manufacturing or overhaul facilities. Alternate matrix field hardware concepts (wire wrap or AMP Term-Point) will provide for fully automatic facilities. This would allow engineering release information for the matrix integration to be made thru punch cards or magnetic tape that could be directly applied to fully automatic tooling for matrix field wiring of the modules.

CONCLUSION

With the increasing involvement of the electrical/electronic systems in both airplane and space vehicles and the criticality of these systems, it is required that advanced wiring techniques and hardware applications be used on an integrated concept. (Figures 16 and 17). Forcing functions in this regard are vehicle manufacturing costs, vehicle weight and total value of technology thru the service life of the vehicle. Key features of wiring of future aerospace vehicles are envisioned to be use of Matrix Units, FCC or ribbon wire trunk bundles, special case usage of multi-conductor SGW bundles, and special designed "fly-by-wire" bundles to assure wiring integrity commensurate to the degree required by the using system.[1,2] Also, flat conductor power feeders will provide significant weight and space benefits as the load requirements increase and as the vehicle configuration requires longer runs.[3] (Figure 18).

The above approach can naturally lead to the next step of Integrated Structure Wiring (ISW). Flat, preformed, multi-conductor cabling appears to be ideally suited to this concept. ISW with properly located Matrix Units would reduce weight, reduce operational costs, and improve integrity. ISW concepts have been studied (Figures 19 and 20). Also, in a number of cases, various programs provided dedicated structural raceways for wiring. An example of this is the "wiring tunnel" from the Thrust Section to the Forward Skirt of the Saturn -1C Booster.

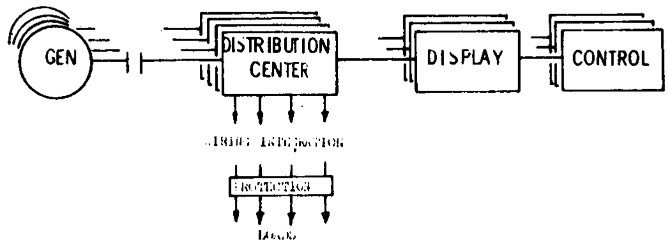
1 Development of Termination and Utilization concepts for Flat Conductor Cables, D6-40711, July 1972, NASA Contract NAS9-10262

2 Electrical Interconnections for Fly-by-Wire Flight Control Systems, USAF Technical Report AFFDL TR-70-134, October 1970

3 Flat Conductor Cable Application for Airplane Power Feeders, Julian Morris, The Boeing Company, Atlantic City Wire & Cable Symposium, December 1970

FIGURE 16

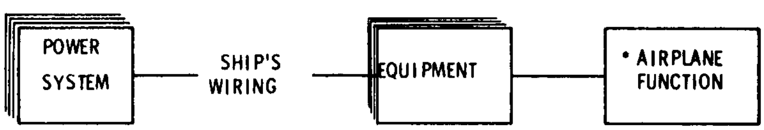
ELECTRICAL SYSTEM TECHNOLOGY



GENERATION-PROTECTION-WIRING-MANAGEMENT

FIGURE 17

TYPICAL FLIGHT CRITICAL FUNCTIONS



AIRPLANE STABILITY

AIRPLANE GUIDANCE

PRIMARY FLIGHT INSTRUMENTATION

ENGINE CONTROLS

MATRIX INTERCONNECTION CENTER

FIGURE 18

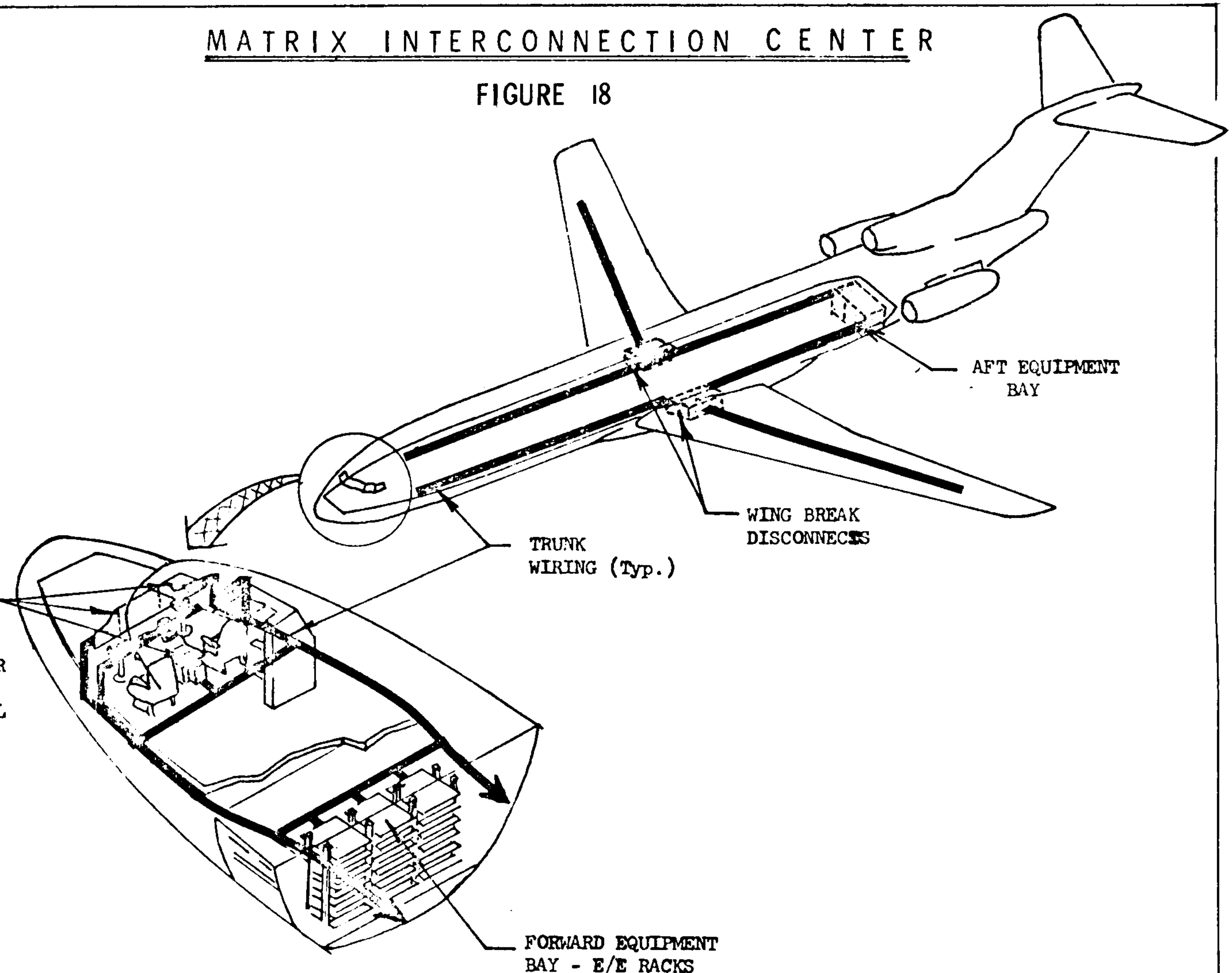


FIGURE 19
INTEGRATED STRUCTURE WIRING (ISW) INSTALLATION

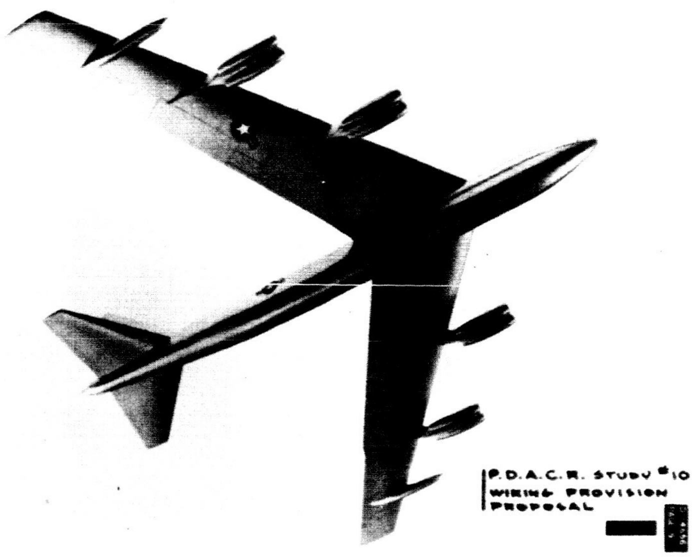
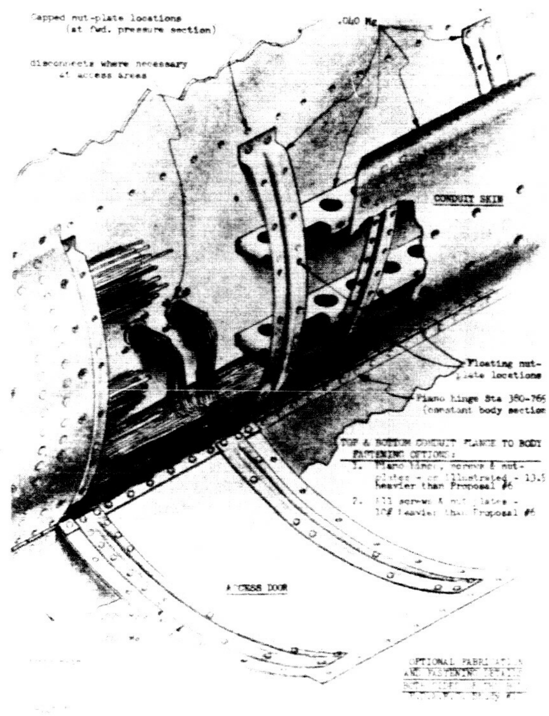


FIGURE 20
ISW DETAILS



CONCLUSION (continued)

In summary, it is noted that the expected payoffs for use of Advanced Wiring Techniques and Hardware Application are:

1. Over 50% labor savings in the fabrication of FCC Trunk Bundles as compared to conventional bundles.

2. Over 50% labor savings in circuit changes for both the Air Frame Manufacturer and the Operator by providing Matrix Units.

3. One Hundred Pounds or greater weight savings per vehicle (minimum of 250,000 feet wire usage) by use of FCC Trunk Bundles, SGW multi-conductor cable and FCC power wiring.

4. Improved capability for tracking circuit changes. Modules may be checked out on a special tester to define exact configuration.

5. Improved wiring system integrity by use of "Fly-by-Wire" wiring techniques as applicable for the using system (USAF Technical Report AFFDL TR-70-134 dated October 1970).

It should be remembered that if the "Wiring Fraternity" within the Aerospace Industry does not provide adequate advances, the only alternatives will be either excessive wiring congestion and weight or multiplexing. This may cause over-use of multiplexing without a satisfactory balance of wiring technology to make proper trades between the two approaches.

The willingness of the industry (Military-Services, NASA Agencies, Airframe Manufacturers, and Component and Wire Suppliers) to accept this development challenge within the next two years (1973 and 1974) will determine whether new airplane and space programs scheduled for initial service in the period from 1975 to 1980 will enjoy the benefits derived from application of an Advanced Wiring System as described herein.

ACKNOWLEDGMENTS

Mr. R. W. Newton of Manufacturing Research & Development Group - Boeing, CAG, has contributed significantly to the culmination of this program.

AMP, Inc., Burndy Corp., and ITT-Cannon have participated in support of the ADEDS Matrix Unit Development Program.

STATUS AND AVAILABILITY OF FCC HARDWARE

By G. K. Romriell
North American Rockwell

NORTH AMERICAN ROCKWELL CORPORATION
SPACE DIVISION
DIVISION PURCHASING

FLAT CONDUCTOR CABLE SYMPOSIUM AND HARDWARE EXHIBIT

MARSHALL SPACE FLIGHT CENTER
OCTOBER 10, 11, 12, 1972

INTRODUCTION

Historically, connectors have been a prime problem source in the procurement of reliable units. Now that Flat Conductor Cable (FCC) is under consideration for future programs, the source availability of FCC connectors is being questioned.

Purchasing was requested to survey the industry to gather information concerning the "state-of-the-art" in this field. Inquiries were submitted to thirty-three suppliers of FCC and/or FCC connectors.

The areas of particular interest are as follows:

1. Cost of FCC versus standard round cable.
2. Qualification status.
3. Size of wire available in FCC.
4. Availability of hermetic connectors for FCC.
5. Conversion from flat cable to round cable and visa versa.
6. Availability of shielded flat cable for RF usage.
7. Termination techniques.
8. Repair techniques.

Of the thirty-three suppliers contacted, the eight listed below responded with affirmative information.

AMP, Incorporated
Bendix Corporation, Electrical Components Division
Cambridge Thermionic Corporation
Cinch-Nuline
Coleman Cable & Wire Company
Hughes Aircraft, Connecting Devices Division
Microdot Inc., Connector Division
ITT Cannon Electric, Phoenix Division

The following pages outline information submitted by these suppliers.

1. Cost of FCC Versus Standard Round Cable

   a. FCC cables are more expensive - about three times the cost of round conductor based upon equivalent conductor cross-sectional areas. (Cinch-Nuline)

   b. Costs can be properly evaluated only on the basis of installed costs rather than a per foot basis. (Coleman)

   c. In a simple cable assembly the costs of FCC are approximately 25 to 30 percent less than round cable (ITT Cannon)

2. Qualification Status

   a. FCC built by Coleman (Micro Cable Division) has been approved for space requirements under NAS 729 and MSFC 220B. (Coleman)

   b. ITT Cannon is presently in the process of performing qualification tests per MIL-C-55544. Qualification is being performed through the Defense Electronic Supply Center (DESC) in Dayton, Ohio. Qualification is expected by January 1973.

3. Size of Wire Available

   a. The range of sizes is essentially unlimited.

   b. An attempt by the industry to standardize FCC has led to the publication of MIL-C-55543.

4. Availability of Hermetic Connectors

   a. No hermetically sealed connectors available for use with FCC. (Cinch-Nuline)

   b. Available on a custom basis. (Coleman)

   c. There are few connectors on the market available for FCC. (ITT Cannon)

   d. "We feature the capability of terminating FCC to <u>any</u> connector." (ITT Cannon)

   e. Not available but could be produced in socket contact side only. (Microdot)

5. Conversion from Flat to Round Cable and Visa Versa

   a. No acceptable techniques or hardware conversion from flat to round or visa versa are known to exist. (Cinch-Nuline)

b. The conversion from flat to round and visa versa is very readily and easily accomplished. (ITT Cannon)

c. Microdot "Micromate" (round cable) is fully intermateable and intermountable with "Flexmate" (FCC) series. (Microdot)

6. Is Shielded FCC Available for RF Usage?

a. Yes. Available from many manufacturers.

b. ITT Cannon, Phoenix, features the capability of laminating shielding to FCC to satisfy EMI problem areas. (ITT Cannon)

7. Termination Techniques

a. Fully automatic machine for termination of FCC offering speed and economy. Eliminates need for expensive and time-consuming cable preparations. (AMP)

b. Conventional production techniques such as soldering, brazing and welding to terminals or connectors. (Cinch-Nuline) (ITT Cannon)

c. FCC is capable of being terminated automatically due to the precise location of all conductors.

d. "We feel that the weld termination is positively the most reliable from an electrical standpoint in that the electrical loss across the welded joints is vertually immeasurable. From a strength standpoint, the electrical joint is stronger than the conductor itself." (ITT Cannon)

8. Repair Techniques

a. Repair techniques usually fall in two categories:

(1) Insulation - can be repaired by using over film and suitable adhesive or potting compounds.

(2) Conductor - usually calls for soldering a jumper. (Coleman)

b. Repair by patch both in the field and in factory. However, this is an undesirable technique. Preferable to design lengths of cable for a given application in modular form. (ITT Cannon)

9. Other Pertinent Information Concerning the Use of FCC

a. Weight reduction not the consideration it has been in the past due to the advent of the superior thin-walled insulations used with round wire. (Bendix)

b. The prime advantage of FCC is its capability of being automatically terminated. (Bendix)

c. The Microdot "Micromate" connector can be used with either round or FCC.

d. Use of FCC can eliminate up to 85 percent of conventional cable weight.

e. FCC can cut cable space requirements 25 percent or more of what they would be with conventional cable.

f. Consistent electrical characteristics.

g. Easy, effective shielding.

FINDINGS

1. The 1971-72 EEM listed 38 companies as manufacturers of flat cable connectors.

2. The 1972-73 EEM listed 33 companies as manufacturers of flat cable connectors.

   a. Only 11 companies repeated.

   b. Twenty-seven companies were removed from the list.

   c. Twenty-one companies were added.

LOW VOLTAGE FCC FOR HOME AND BUSINESS

By L. Wolf
Hobby Hill, Inc.

1. Introducing our flat cable which we call CONDUCT-O-TAPE — a thin, pressure-sensitive conductor for low voltage uses.

2. First, I'd like to give you a little run down on how we created this thin, flat cable:

HOBBY HILL, INC. is the manufacturer of the brand name:

- o HANG-O-LITE Picture Lights
- o CURL-O-LITE and SHELF-O-LITE for cabinets and shelves.
- o Wiring harnesses to specifications for special purposes.

3. Our regular line of Hang-O-Lites have cords showing — not too bad where the cords are hidden by a piece of furniture, sofa or cabinet of some kind. However, too frequently there are areas where the cords are exposed like a sore thumb.

Due to this, we have had constant requests from our customers asking for battery operated picture lights.

We hired an electronic R&D company to help us develop a battery operated light.

When completed, this transistorized battery picture light used nickle cad. cells, packed flat to hide behind the picture.

The light would give a period of about 6 hours lighting.

The cells had to be removed after each evening's use, placed in a charger for 10 to 12 hours for re-charge and then replaced into the picture light.

We decided that all this, just to light up a picture, did not make good sense....besides being very expensive for the market.

4. We combined the use of a high intensity light.

A transformer

And a very thin conductor for the hook-up (pressure-sensitive tape).

Two ribbon copper conductors applied to the adhesive side of the tape.

We use mylar film.

5. If properly prepared, the tape conductor can be painted or wallpapered.

CONDUCT-O-TAPE by itself was useless with terminals to make simple, fool-proof connections.

We designed the tape terminals

The straight splices to add tape to tape.

The "L" splice to go around doorways

And wire terminals to hook-up wire to the CONDUCT-O-TAPE.

6. These are the CONDUCT-O-TAPE terminals:

(a) Strip off the release paper and expose the 2 copper strips.

(b) Attach the CONDUCT-O-TAPE to the terminals, copper to copper.

There is no adhesive on the copper itself.

7. (c) Turn it over and remove the release paper on the opposite side, exposing pressure-sensitive surface.

(d) Attach the completed tape and terminal to the desired surface.

(e) If the surface is metal, you can apply a plain pressure-sensitive tape to the surface first —

Or we can make the CONDUCT-O-TAPE with a mylar surface on both sides of the copper with pressure-sensitive on the bottom.

8. These are the straight splices — continuous splicing material:

Same procedure is used as with the terminals

(a) Remove release paper

(b) Apply CONDUCT-O-TAPE to 1/2 of the splice.

(c) Apply other CONDUCT-O-TAPE to other half of splice — copper to copper.

(d) Remove release paper from other side — attach to surface.

9. Plug in the wire terminal and you have a complete flat cable hook-up.

Almost no thickness

When painted or wallpapered is not visible.

10. The tape can be applied around doorways.

11. Angle splices are treated same as straight splices.

(a) Attach copper to copper

(b) CONDUCT-O-TAPE should be cut at a miter.

12. Remove release paper from other side

Turn over and apply to surface.

13. When a room is wallpapered, CONDUCT-O-TAPE is applied in the following manner.

14. Slit the paper with a sharp knife or razor blade.

Peel back.

15. Apply the CONDUCT-O-TAPE to wall.

16. Then apply double faced tape and replace the wallpaper —

17. Leaving the top and bottom tape terminals exposed

(a) Top terminal is for high intensity lamp

(b) Bottom for transformer.

18. This shows a unit with tape applied to a walnut paneled surface —

Yes....you cannot see the tape, that's true.

We applied a walnut contact tape over the CONDUCT-O-TAPE to match the surface.

Still very thin.

It is hardly visible.

There are wood grain contact tapes to match practically all wood panels.

I am pointing to the tape application

19. Here it is again —

(a) The complete unit showing the transformer at the baseboard.

(b) It has a tip-toe switch built in for easy access.

20. Now compare this with the unit using actual wire.

Even the amount of light compares favorably with a unit using actual wire.

21. CONDUCT-O-TAPE consists of a mylar film with pressure-sensitive surface.

Copper is applied to the pressure sensitive side.

The other side has a special prepared surface to take paint.

It can be painted separately and applied to surface that has been previously painted.

22. These are some of the components

Tape terminal splice

Straight splice

Angle splice

25 roll CONDUCT-O-TAPE

Wire with plug-in terminal

Dispenser has 200 feet CONDUCT-O-TAPE. (Also comes in 500 foot rolls)

The wide tape below the larger roll is 300 ohm tape and 3 wire tape.

For television lead-in wire and also

For dipole aerials

Transformer is 118V - 60 cy. with built in switch and breaker

Several of our prominent radio companies are preparing to market —

23. CONDUCT-O-TAPE for stereos

24. And the new Quadrosonic sets.

25. CONDUCT-O-TAPE can be made up various ways

(a) 18 ga. equivalent
20 ga. equivalent
24 ga. equivalent

(b) Film on both sides

(c) Wide - 300 ohm
Wide - 3 wire leads and more

(d) CONDUCT-O-TAPE is being used for

- Picture Lights
- Doorbells
- Speaker Systems
- Stereos
- Quadrosonics
- Telephones
- Intercoms
- Thermostats
- Burglar Alarms
- Toys

I am sure there are many other uses for this handy wiring system.

We hope that you, too, will come up with suggestions for use in other fields.

You may rest assured that we will give you our full cooperation and help in any way possible.

If you require further information, please let us know.

We have a sample kit of CONDUCT-O-TAPE for each of you. If per chance you do not get one, please leave me your card and I will see to it that one is forwarded to you.

Also, if you want to be placed on our mailing list, please leave me your card.

Thank you for your kind attention during my presentation.

Hobby Hill, INC. 417 North State Street • Chicago, Illinois 60610 • Phone (312) 944-2144

INVISIBLE LOW-VOLTAGE WIRING (FLAT CABLE)

Just the ticket for a neat speaker installation or adding intercoms, doorbells, burglar alarms, clocks, etc. without running wires between walls.

Two thin strips of copper bonded to a pressure-sensitive plastic strip makes up the wire tape. Just peel off the backing, apply strip to surface and paint or wallpaper over it.

You can even run this tape under the carpet without creating a tell-tale hump.

CONDUCT-O-TAPE - pressure sensitive tape with copper conductors on the adhesive side. When applied to a surface - it is extremely flat - can be painted or wallpapered over -becomes practically invisible.

It is easy to apply. Straight splices for adding on and corner splices for going around doorways, windows, etc. Female connectors with built-in spring tension attached at both ends, makes it simple to plug into or disconnect terminals.

FILM -Mylar.... .001 x 5/8". Adhesive - non-corrosive rubber base. Cures to attached surface in approximately 24 hrs. Outer surface -coated to take paint.

COPPER -soft -flat..... .0032 x .063. Equivalent to 24 guage wire. rated at 3 amps.
SPECIAL ORDERS :
7/8" wide tape..... approximate 18 guage equivalent copper tape -- 3 conductor tape -- 300 ohm tape for TV lead-in.

Standard rolls : 5', 10', 25', 50', 100', 200', 500'. Available Bulk Pack or Point of Purchase Display.

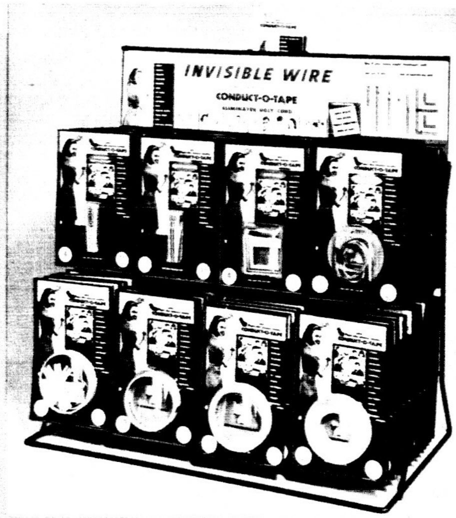
INVISIBLE WIRE

Paper-thin, pressure-sensitive

CONDUCT-O-TAPE

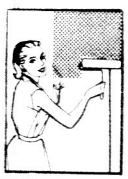
PATENTED

ELIMINATES UGLY CORD

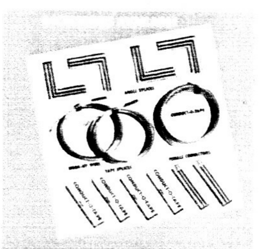


FOR LOW VOLTAGE

- STEREOS
- SPEAKERS
- INTERCOMS
- TELEPHONES
- DOORBELLS
- GAMES
- TOY TRAINS
- SCONCES
- ELECTRONICS
- RADIOS
- BURGLAR ALARMS
- SIGNAL BOARDS
- CLOCKS
- WINDSHIELD ANTENNA
- PICTURE LIGHTS
- CURIO LIGHTS



PAINT WILL COVER

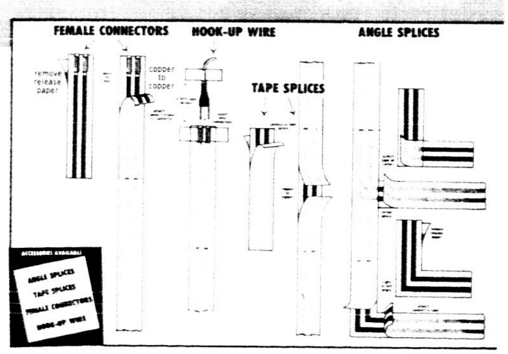


It has a pressure sensitive adhesive which when applied to surface creates a permanent bond. The surface of CONDUCT-O-TAPE is specially treated to take paint. When coated with roller or brush, most paints will hide or cover with one coat.

Unlimited treatments are possible with CONDUCT-O-TAPE, such as: hookup of extension speakers to stereos; one can go around doorways, windows, cabinets, under carpeting, over woodwork, etc.

For autos, it can be applied to the inside of a windshield and it becomes a car "window antenna", replacing the fender antenna. Actually improves reception.

Special connectors are available which make hookups very simple. Angle splices for doorways can make left or right angles. Same angle splices can be used for inline connections. Straight splices are also available and enables one to add on extra lengths.




HIGH INTENSITY PICTURE LIGHT ELIMINATES UGLY CORD
Paper-thin, pressure-sensitive
CONDUCT-O-TAPE
PATENT PENDING
PAINT OR WALLPAPER WILL COVER
THE ORIGINAL Hang-o-Lite PICTURE LIGHTS
*ATTACH CONNECTOR TO WALL
Strip release paper from connector
Attach to wall back of picture
Strip release paper from CONDUCT-O-TAPE
ATTACH TRANSFORMER TO BASEBOARD OR WALL
Strip off green release paper.* Press to wall -- It will hold
Insert thin wire into bottom connectors.
ATTACH HANG-O-BRACKET TO FRAME
CONNECT WIRE TO TOP CONNECTOR
Hang up picture and picture light.
PLUG IVORY WIRE INTO OUTLET
Press switch on top of transformer.
Press again to turn light off.
CONDUCT-O-TAPE can be painted or papered over.*
YOU NOW HAVE A PICTURE LIGHT WITHOUT A CORD SHOWING!
*IMPORTANT
Make sure wall surface is free from dust and oil.
Do not finger tackey side of tape or splice.
Because CONDUCT-O-TAPE has a permanent curing adhesive, it should not be reused once it is applied.
When painting CONDUCT-O-TAPE — do not paint connectors.
CONDUCT-O-TAPE is made for LOW VOLTAGE ONLY.
YOUR DEALER CAN SUPPLY YOU WITH ADDITIONAL TAPE OR SPLICE MATERIAL
©1970 Manufactured by HOBBY HILL, INC., 417 N. State Street, Chicago, Ill. 60610 (312) 944-2144 Printed in U.S.A.

CONDUCT-O-TAPE

PATENTED

(Low voltage conductor)

SPECIFICATIONS

CONDUCT-O-TAPE - pressure sensitive tape with copper conductors on the adhesive side. When applied to a surface - it is extremely flat - can be painted or wallpapered over - becomes practically invisible. It is easy to apply. Straight splices for adding on and corner splices for going around doorways, windows, etc. Female connectors with built-in spring tension attached at both ends, makes it simple to plug into or disconnect terminals.

FILM

Mylar.................................... .001 x 5/8"
Adhesive - non-corrosive rubber base.
Cures to attached surface in approx. 24 hrs.
Outer surface - coated to take paint.

COPPER

Soft, flat.................................. .0032 x .063
Equivalent to 24 guage wire.
Rated at.................................. 3 amps.

SPECIAL ORDERS

Approx. 18 guage equivalent copper tape...... 7/8" wide

3 conductor tape......................... 7/8" wide

300 ohm tape for TV lead-in................ 7/8" wide

Standard CONDUCT-O-TAPE available in rolls:

5', 10', 25', 50', 100', 200', 500'

Available Bulk Pack or Point of Purchase Display.

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FCC FOR HOMEWIRING

By J. Hankins
NASA-MSFC

SURFACE MOUNTED FLAT CONDUCTOR CABLE FOR HOMEWIRING

INTRODUCTION

When Flat Conductor Cable (FCC) for Homewiring is first discussed with someone, their first two questions are usually: 1. Why is NASA involved in housewiring? and 2. Is it safe? What happens if you drive a nail through it? The first question is usually "not-voiced" --just a look of puzzlement and curiosity. The second question comes through loud and clear, with definite tones of doubt and concern. Both of these questions, and others, will be answered in the following pages of this report.

Even though NASA missions are space oriented, this is not the first time that commercial applications and spin-offs have evolved from NASA projects. By encouraging secondary applications of aerospace technology, NASA can reduce industry's duplication of research effort, while increasing the return on the taxpayer's investment in the national space program.

The NASA Technology Utilization (TU) Program, was specifically established to identify and transfer NASA technology to the public sector. To accomplish this, each NASA center has a TU Office which works jointly with the Headquarters TU Office in Washington, D.C. The Headquarters TU Office, through an Urban Development Application Project (UDAP), is trying to help the overall building industry by applying aerospace technology to many construction problems. Abt Associates, Cambridge, Mass., has been commissioned to carry-out UDAP. Through their discussions with the New York Urban Development Corporation, and other building organizations, it was made known that drastic improvements and changes must be made in homewiring to cope with <u>increasing material and labor cost</u>, <u>increasing electrical demands</u>, <u>new building materials</u>, <u>new concepts of building</u>, and <u>rehabilitation of old buildings</u>. The NASA Flat Conductor Cable development group was contacted and asked if FCC might be an answer to some of the homewiring problems. As a result, Engineers at Marshall Space Flight Center (MSFC), through the various TU Offices, are actively pursuing the application of Flat Conductor Cable Technology to a SURFACE MOUNTED HOMEWIRING SYSTEM. The new system, which is now in the conceptual phase, will satisfy the wiring requirements throughout the entire house; e.g., the kitchen, the dining room, the den, the bedroom, and the bath. The planned system will be total FCC; <u>from</u> where the service line enters the power panel (such as the concept shown in figure 1), <u>throughout</u> the

house--to lights, switches, and special wiring; including telephones, intercoms, and alarms--, to where the system interfaces with standard plugs (figure 2), or equipment and appliance terminations.

In developing the new system, four things must be achieved:

1. It must reduce overall cost.

2. It must be functional.

3. It must be as safe or safer than present electrical systems.

4. It must be aesthetically acceptable.

MSFC Engineers feel that such a system is not only feasible, but will be developed in the next few years. It is interesting to note, that FCC for homewiring is not new. In 1884, Charles Temple Jackson, was granted the first patent for FCC for homewiring. He laminated flat copper conductors between thin strips of paper, and cemented it to the wall. Now, flat conductor cable is usually made of rolled or slitted flat conductors, laminated between thin, flexible, plastic, insulating films. Up until now, practically nothing has been done to adapt FCC to homewiring. There have been some communication and electronic console type applications, but these were mostly low voltage with small conductors. The time is now right to revolutionize our homewiring systems. The materials and manufacturing know-how are available; a "Surface Mounted Flat Conductor Cable System" can be the answer.

BASEBOARD CONCEPTS

So far, MSFC Engineers are considering two types of BASEBOARD SYSTEMS for distribution of power throughout a given room, or the entire house if need be. The first is a SNAP-ON COVER SYSTEM (figure 3). A typical installation sequence would be as follows:

1. Install wall clips or other suitable attachment hardware.

2. Route and Install Cable. Note that this is done by layers, and the circuit is continuous--no joints, except at the beginning or ending of a run.

3. Attach receptacles at desired locations.

4. Snap on appropriate corners--inside and outside.

5. Cut baseboard to length.

6. Remove knock-outs from baseboard mold to align with the receptacle face.

7. Snap on baseboard mold.

Receptacle attachment for the Snap-On Cover System can be made by several methods, including: crimping, soldering, riveting, and stapling (figure 4), or by pressure contact on the "bared" conductor (figure 5), or even through the insulation.

The Snap-On baseboard system will accommodate several layers of cable, probably up to six without difficulty. It can be put on the market quickly, because very little development is needed, and the design is simple. It would require more on-site installation manhours than an Extendable Baseboard System (figure 6 and 7).

The components for the EXTENDABLE BASEBOARD SYSTEM would be factory-made--maybe automated to eliminate manual labor. Typical components would be: inside corners, outside corners, end caps, adapter junctions for FCC, adapter junctions for round wire, and extendable baseboard sections which come complete with receptacles. The extendable sections would be available in several "size-ranges" so that any wall length can be fitted. The concept in figure 6 has receptacles for standard 3-prong plugs. The system in figure 7 is much thinner and requires an adapter which plugs into the top of the extendable section. A typical installation sequence for either Extendable Baseboard System would be as follows:

1. Install attachment hardware--simple clips or snaps; maybe an adhesive on the baseboard back, with peel-off paper.

2. Plug the components together.

3. Telescope the sections to length.

4. Place onto the wall.

As can be easily seen, the extendable system will require more development and design, than the snap-on cover system. It has more joints, which means that each joint must be highly reliable; but even with the extra joints (2 per corner per conductor), the FCC Extendable Baseboard will have fewer connections that existing round wire systems, which have at least 2 joints per receptacle per conductor.

Surface Mounted FCC Homewiring Systems will be safe--equal to or better than existing homewiring methods. Although FCC is completely "electrical-compatible" with homewiring requirements (voltage, current, insulation resistance, etc.), some problems do exist in making it safe and minimizing electrical shock.

There are three controlling factors which determine the physiological effects of electrical shock on people:

1. Body Weight

2. Current through the Body

3. Duration of Shock

The physiological effects of electrical shock (figure 8) vary, from barely susceptible sensation to DEATH. The effects shown in figure 8, and the corresponding milli amp levels, apply to most people--but not all. Most people can "let-go" a hot wire at 16 milli amps or less. Ventricular Fibrillation usually causes death between 100 and 200 milli amps, and surprisingly, in the 200 to 1000 milli amp range, severe muscular contractions, forcibly clamp the heart, and protect it from damage. Survival is good if immediate medical aid is given.

Making FCC safe, without using expensive raceways and conduit, is within the state-of-the-art. Several techniques are available by which an FCC Homewiring System can be made safe:

Inaccessibility - This method reduces the probability of a person being accidently shocked. Routing of the cable in corners, above reach-height, at top of walls, on ceilings, in the attic, and in closets are typical examples.

Protective Coverings - It is obvious that metal raceways could be used for routing FCC, but this would not be compatible with lower cost nor aesthetic goals. Figure 9 shows a cross sectional view of how a cable with a "grounded shield" can be installed--surface mounted; the thickness to width ratio is exaggerated for clarity. The shield offers mechanical as well electrical protection, and will do the "trick" as a safety measure, but it has the disadvantage of making the cable about 20 mils thicker, which makes it more difficult to hide under wall coverings such as paint and paper. Engineers have tested the "grounded-shield" concept and found that it works. With the test set-up shown in figure 10, several hundred penetrations were made, using a nail and hammer. A very sensitive memory oscilloscope did not

detect any voltage potential between the nail head and ground. As the nail penetrates the shield and the hot conductor, a short is made which will trip any proper protection device, and because the nail makes continuous contact with the grounded shield, there is no possibility of electrical shock.

Ground Fault Interrupters (GFI's) - These protection devices interrupt or open a circuit when undesired current paths--"faults to ground"--are detected. These faulty paths are frequently people. GFI's are available on the market today. Popular Science, August 1972, contained an article about one being marketed by Square D, with the trade name of Quik-Gard. Ground Fault Interrupters can be easily adapted to FCC Homewiring Systems, however, additional development is needed before the following absolute requirements are fulfilled.

1. The device must fail safe.

2. The device must prevent electrical shocks greater than 10 ma between hot line and ground.

3. The device must be reasonably priced.

Obviously, Combinations of the Above could be utilized if ever required.

STATUS, PROBLEMS AND ADVANTAGES

As stated before, the MSFC HOMEWIRING project is in the conceptual phase, and two contracts (as of October 1972) are in process of being awarded; both are for prototype hardware: One is a circuit breaker panel with a round wire service line and FCC distribution circuits, and the other is a surface mounted baseboard system. The next contract will probably be for: (1) interroom connections, (2) intrahouse cable routing and attachment techniques, and (3) interconnecting devices for equipment and special appliances.

Believe it or not, there will be problems to surmount before FCC is established as a homewiring system, for example:

1. Establishing FCC Electrical Codes

2. Unions and Trades

3. Architect and Engineer Acceptance

4. Manufacturer and Distributor Acceptance

5. Contractor and Utility Company Acceptance

6. Human Resistance to Change

7. Massive Changeover

8. Safety Methods

9. Interroom Routing

10. Funding and Time

This was not intended to be a complete list, but it does indicate that many people, organizations, businesses, companies, manufacturers, and stock holders will be involved. Most of the problems will be "people problems." The seventh problem (Massive Changeover)--changing from round wire methods and hardware to FCC methods and hardware--will be gigantic, and no person alive today will live to see it completely solved. The technical problems, of which two are noted (Safety and Routing), will be very minor as they relate to the first seven problems. The last problem might be more appropriately listed, as the "answer to all problems."

The most significant reason for implementing an FCC HOMEWIRING SYSTEM, is low overall cost to the owner. Typical advantages of an FCC wiring system are:

1. Flexibility

2. Surface Mounted

3. Polarized Wiring

4. Lower Material Cost

5. Lower Installation Cost

6. Less Skill Labor Required

7. Thin or Low Profile

8. In-line Receptacle Installation

All of the advantages shown above support the goal--lower cost. This list, like the previous "problem-list," is not a complete listing. FCC is very Flexible; it easily folds around corners and angles. In addition to lowering new construction cost, Surface Mounted FCC will drastically reduce the electrical cost of rehabilitating and remodeling existing

buildings (homes, offices, schools, apartments, stores, and hospitals). With Polarized Wiring, any "mis-wiring" would be intentional, not accidental; and conductors can be easily traced and identified. Material Costs will be reduced by "using less" in most cases; e.g., with a polarized system, it is conceivable that the third wire (the safety ground) might be eliminated; it is a parallel path back to the same point in the circuit breaker box. Installation Costs will be lowered by minimizing on-site labor. Since the installation is simple, Less Skilled Labor can be used. Less coordination will be involved in scheduling the different trades, such as carpenters, plumbers, electricians, and painters. The Thinness of FCC makes it easy to conceal. For aesthetic reasons, it can be hidden on walls, under paper, under paint, behind paneling, and under floor coverings such as tile, carpet, linoleum, and rugs. FCC can be hidden under most interior--or exterior for that matter--finishes. Thin FCC can be stacked or layered for low-profile routing of many circuits. Receptacle Installation Time will be reduced considerably with the Snap-on Cover Baseboard System (figure 3), and it will be zero with the Extendable Baseboard System (figures 6 and 7).

SUMMARY

As a part of the NASA Technology Utilization Program, MSFC Engineers are in progress towards establishing FCC as a standard homewiring method. Two contracts for prototype hardware are in the mill, and a third contract is being planned. The technical problems involved in completing the Homewiring Project, are within the state-of-the-art. The goal: A Surface Mounted Flat Conductor Cable Homewiring System that is LOWER IN COST, FUNCTIONAL, SAFE, and AESTHETICALLY PLEASING.

The next six figures show some of the past, present and future history of electrical housewiring. Figure 11 shows electrical hardware which is part of the past; but many are still around today. Figure 12 shows hardware which is still standard practice in many cases; an adapter was used in bridging the old with the new. Modern homes now have safe polarized connectors (figure 13), when properly wired. Soon, an adapter (figure 14) will again be used to bridge the gap between the old and the new--an old 3-prong plug and a new FCC baseboard system. It will be an easy and logical transition to establish FLAT PLUGS for round wire (figure 15). In the near future, an electrical housewiring system might be like that shown in figure 16--ALL FLAT.

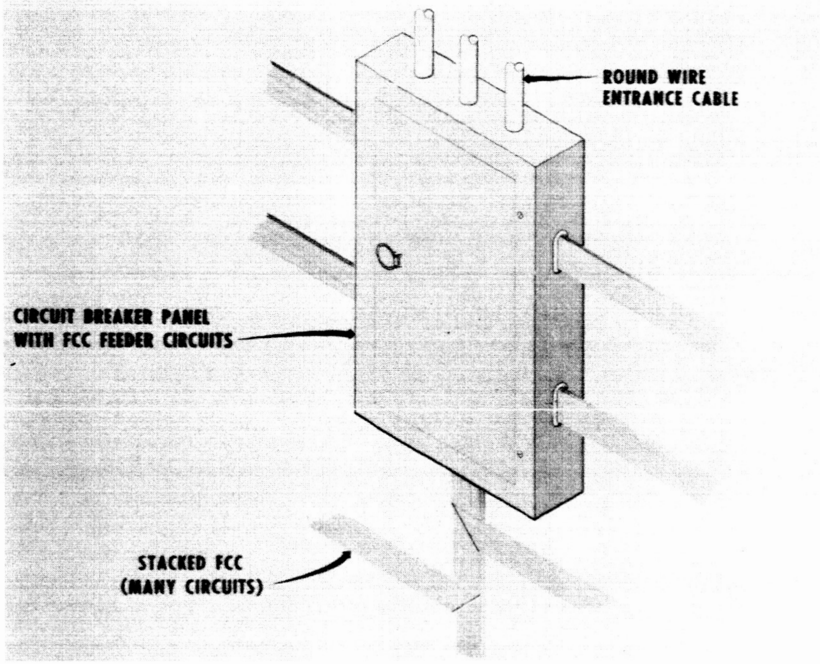


Figure 1. Circuit Breaker Panel

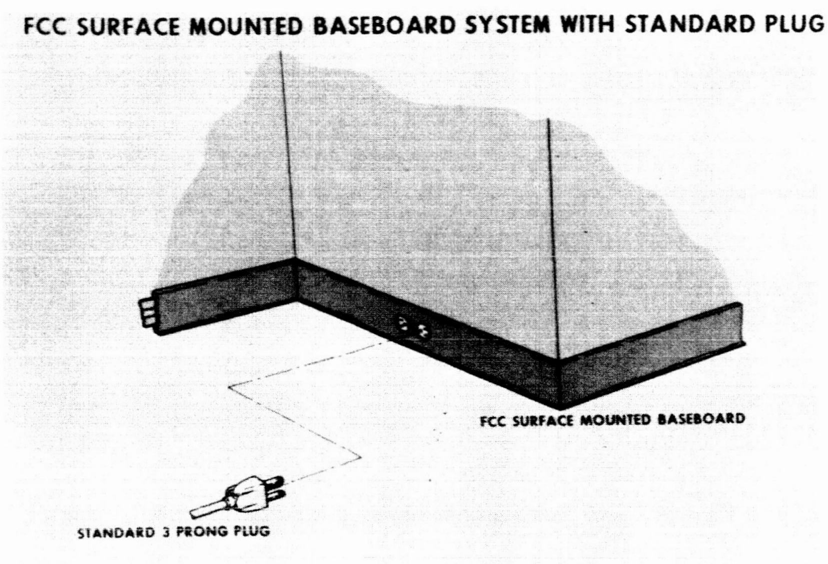


Figure 2. Surface Mounted Baseboard

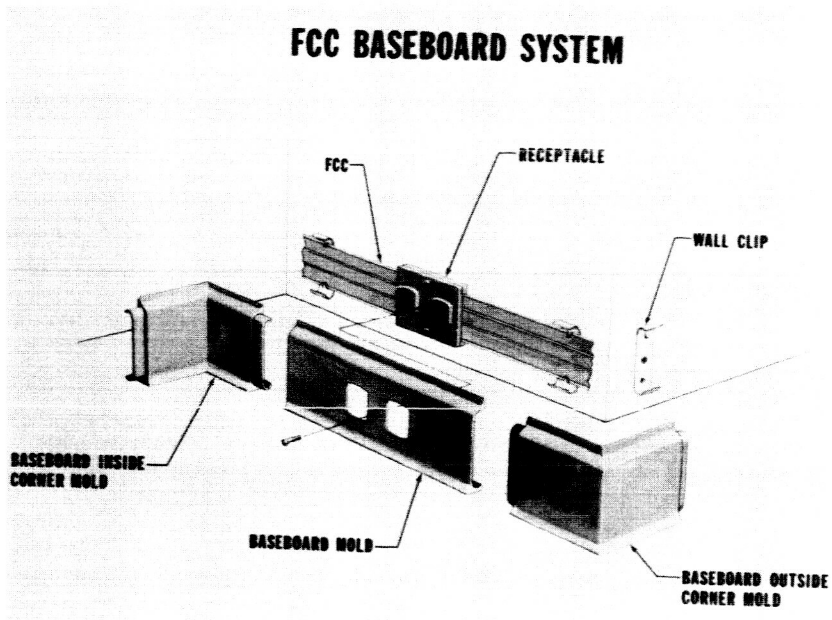


Figure 3. Snap-on Cover Baseboard System

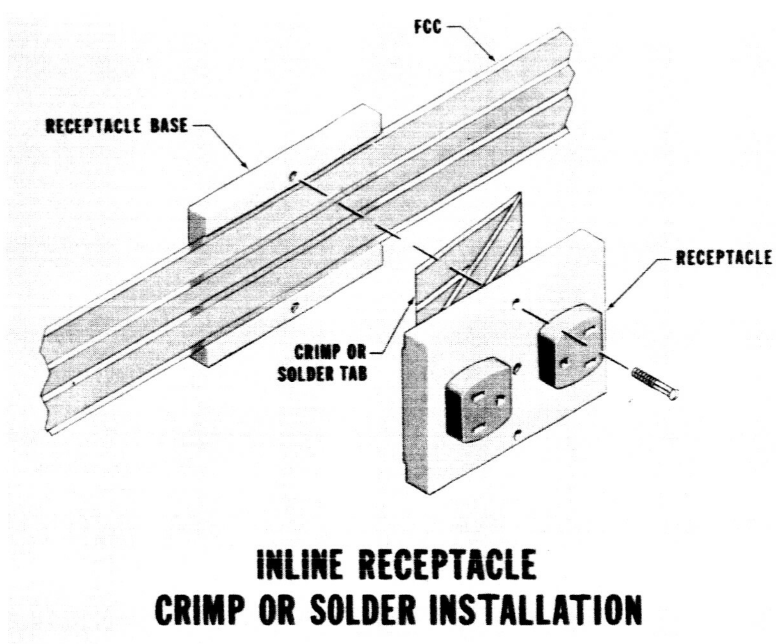


Figure 4. Receptacle with Crimp or Solder Tab

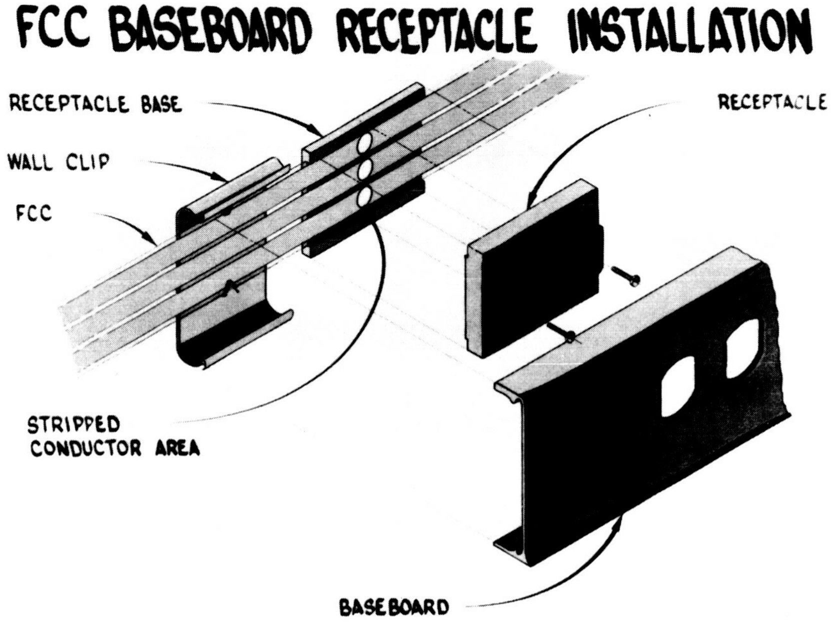


Figure 5. Receptacle with Pressure Contacts

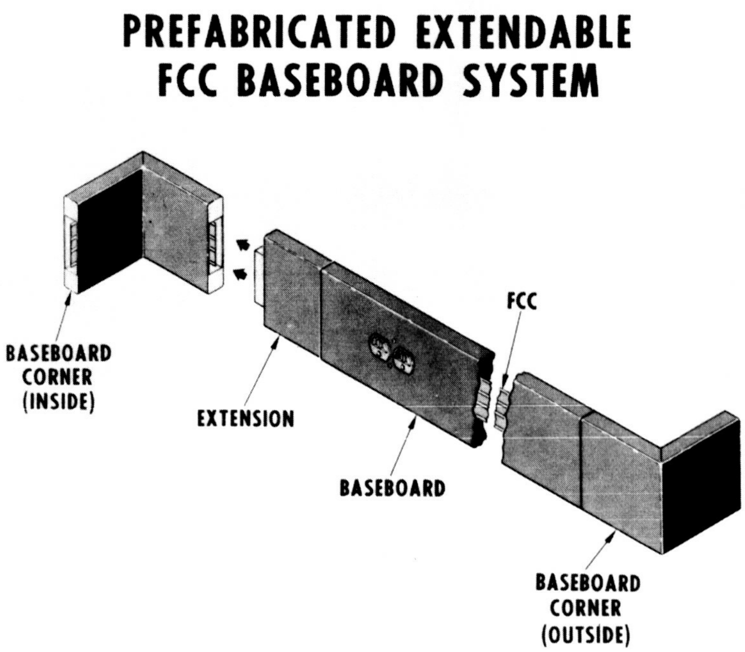


Figure 6. Extendable Baseboard with Standard Receptacle

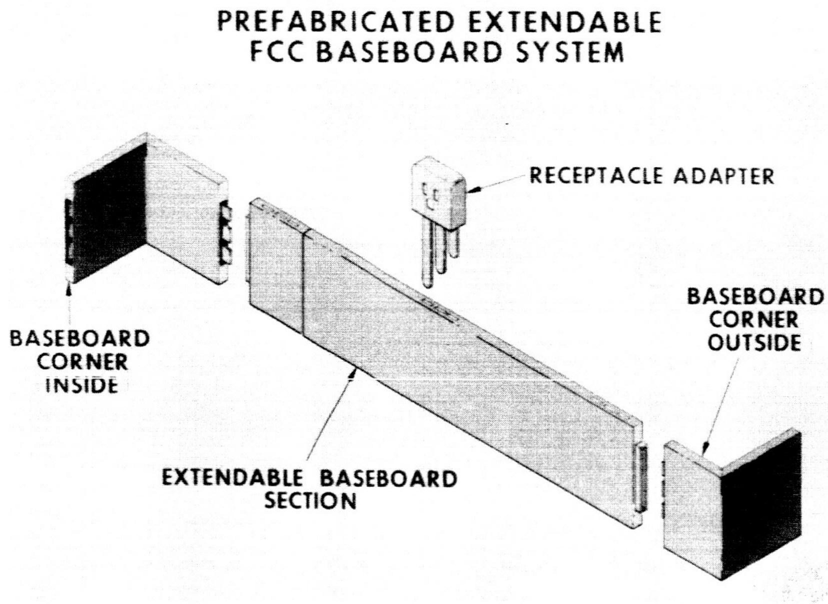


Figure 7. Extendable Baseboard with Adapter

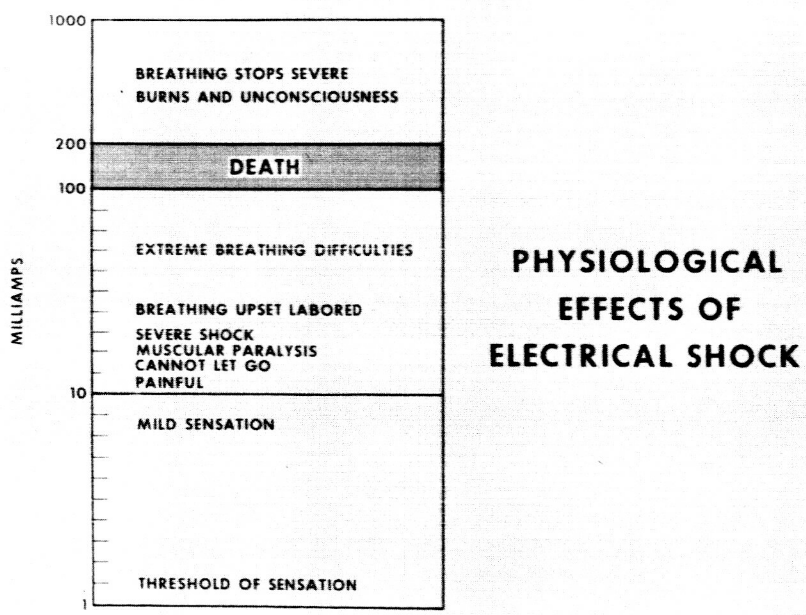


Figure 8. Physiological Effects of Electrical Shock

FCC INSTALLATION WITH SAFETY SHIELD

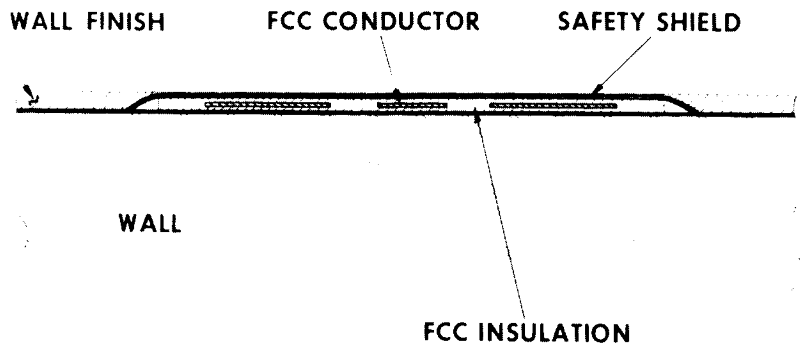


Figure 9. Cross Section of FCC Installed with Safety Shield

FCC SAFETY SHIELD TEST

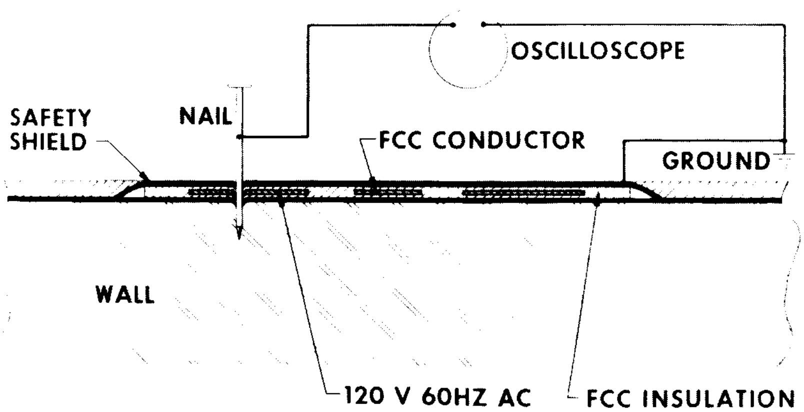


Figure 10. Test Set-up for FCC with Grounded Shield

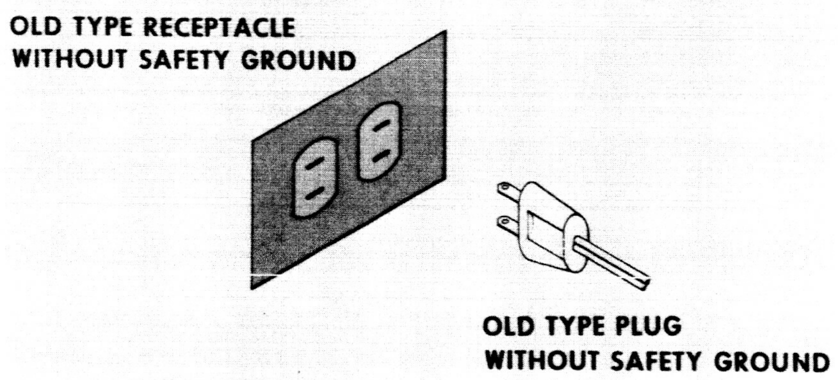


Figure 11. Standard Non-Polarized Duplex Connector

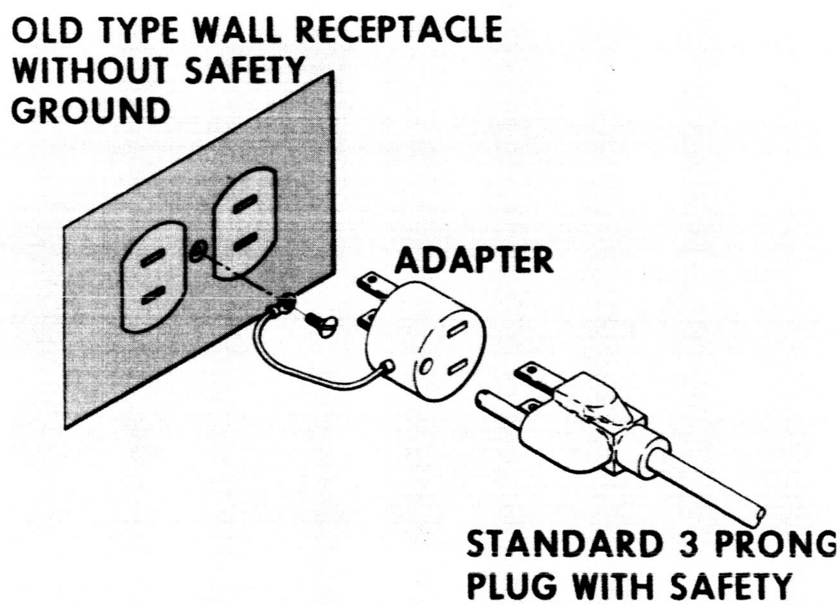


Figure 12. Non-Polarized Duplex Receptacle
with Adapter for 3-Prong Plug

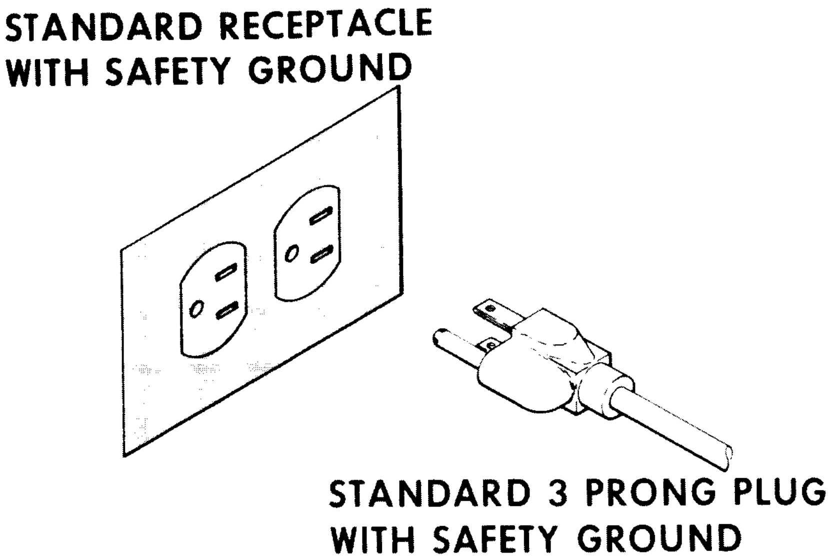


Figure 13. Standard Polarized Duplex Receptacle with Plug

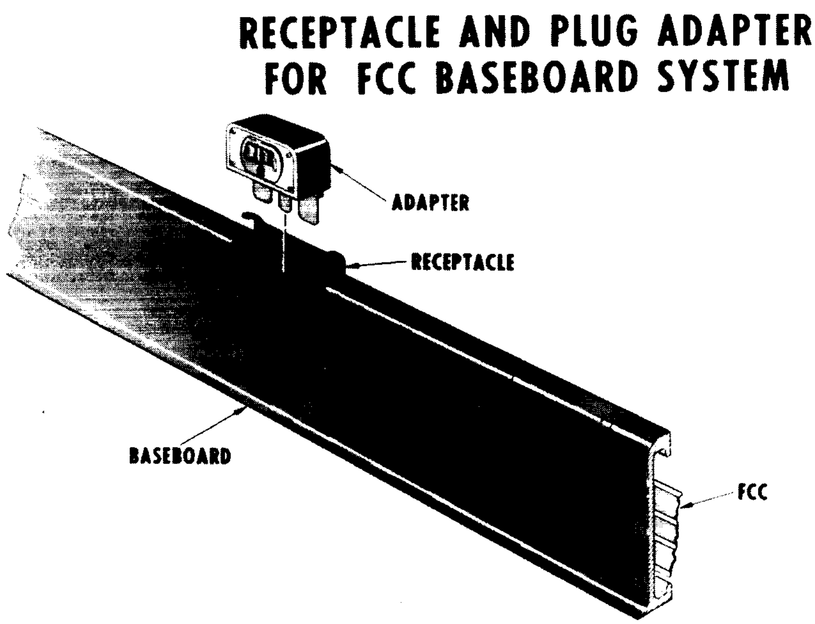


Figure 14. FCC Baseboard with Adapter for 3-Prong Plug

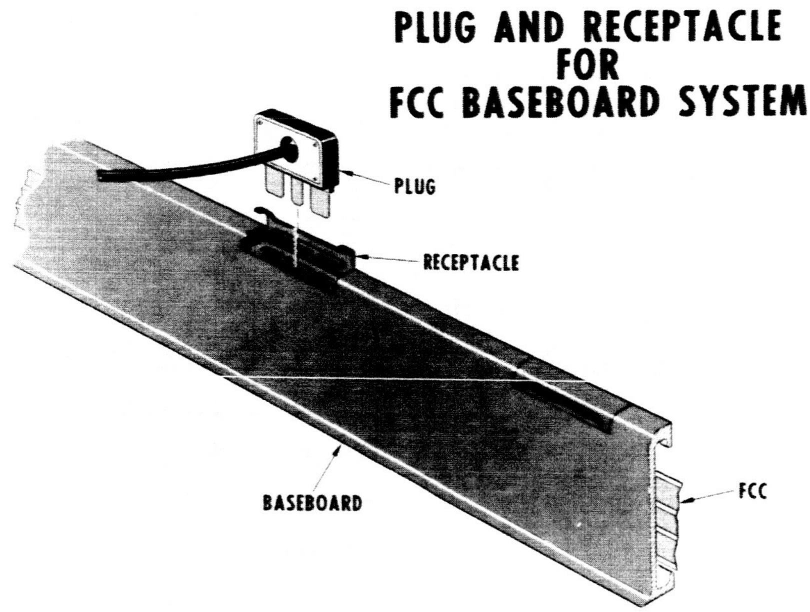


Figure 15. FCC Baseboard with Flat Plug for Round Wire

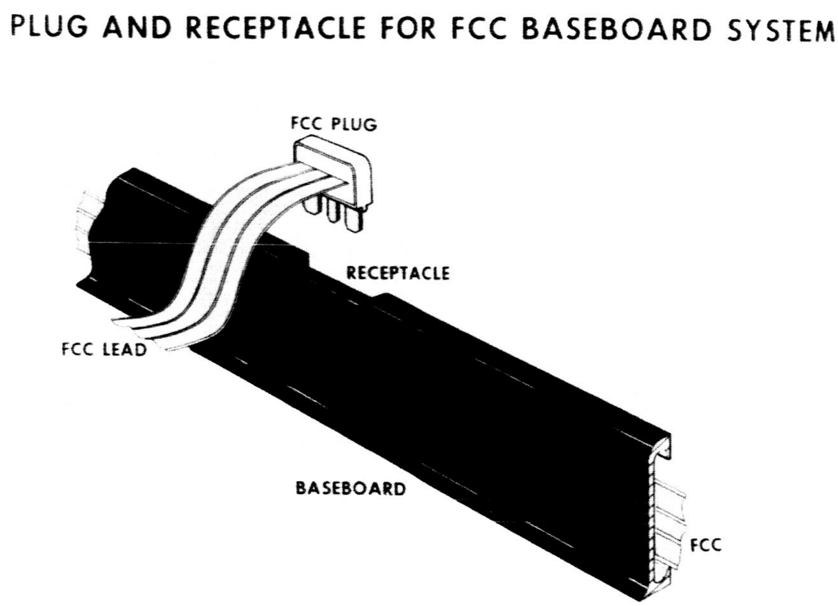


Figure 16. FCC Baseboard with FCC Plug and Cable

FCC FOR ALSEP (LUNAR EXPERIMENT)

By George Cripps
Bendix Corp.

FLAT CABLES FOR ALSEP

Preamble

You have seen the TV coverage of astronauts working on the moon, but relatively little appears in the popular media concerning the Apollo Lunar Surface Experiments Package or ALSEP. Scientists specify high sensitivity and performance for their experiments in the inhospitable lunar environment. Manned Spaceflight Center in Houston requires exceptional reliability to be sure that the scientific objectives are met. All the ALSEPs are still working with the Apollo 12 system, having 3 years of service.

Slide 1.	ALSEP — LM view
Slide 2.	ALSEP down sun
Slide 3.	Comparison of cable memory on earth
Slide 4.	Cable requirements
Slide 5.	Flat-round comparison
Slide 6.	Disadvantages of flat cable
Slide Blank	Demonstration of reeling
Slide 7.	Crosstalk suppression
Slide 8.	Signal arrangement
Slide 9.	Cable tearing
Slide 10.	Cable performance unstowed
Slide 11.	Section through connector
Slide 12.	Sharp pin problem
Slide 13.	Rounded profile
Slide 14.	Summary
Slide 15.	The future

Notes for Slides 1, 2, and 3

Explain ALSEP

Apollos 12, 14, 15, 16, and 17 – Superreliable, all used flat cables

High reliability – Apollo 12 has 3 years service

High sensitivity

Slide 2 – PSE recorded astronauts in LM ALSEP comprises:

High reliability central station

5 experiments

Thermopile power source – 70 W

Small antenna transmits data to MSFC-Mission Control

Scientists control experiment operation and temperature from Houston

+250 to -300°F

Eclipse – 556° F/hour

Slide 3 – Memory of cable

ALSEP Introduction

The crews of Apollos 12, 14, 15, and 16 deployed ALSEP packages on the moon. Each package comprises a high reliability central station and five experiments. Power is supplied by a thermopile, excited by a radioactive fuel element giving 70 watts of useable power. A small helical antenna transmits experiment science data, engineering, and status information back to the Manned Space Flight Network of receiving stations. Ground stations transmit command messages originating in Mission Control in Houston. These commands are used by the Principal Investigators to optimize the data-gathering function of their experiments and by the mission controllers to operate redundant elements and power so that the thermal excursion is limited. Lunar

surface temperatures reach +250°F at lunar noon and -300°F at night. All exposed equipment including cables must withstand these extremes and also the hundreds of degrees per hour thermal shock that occurs during an earth eclipse of the moon. An actual 556°F was recorded.

ALSEP experiments are spread out to minimize interaction requiring long cables that can be deployed by a single astronaut.

Cable Requirements

Wide thermal range

Single astronaut deployment

Light weight

Small volume

Little "memory"

Trade-off with Round Wire

If a constant conductor cross-section is assumed as a basis for a 40-conductor cable carrying power supplies, and analog and digital signals with a length of 40 feet, then the following observations can be made:

1. Both cables can operate over the temperature range and can resist the solar UV radiation.

2. It was thought that the lunar surface may comprise sharp rocks so the cable must withstand being stepped on by the astronaut.

3. Round wire cables have substantial memory and would remain in large loops, whereas flat cable can be made to flatten with a little tension. A particular round cable between an experiment and sensor continually defied astronaut attempts to keep the experiment vertical. In earth gravity, the sensor weight was six times greater and the problem did not show up.

4. Weight of the flat cable, connectors, and stowage reel was 8 pounds but the equivalent round cable assembly weighed over 25 pounds. The increase in weight is mainly caused by the need for shielding with round wires. Volume of the round wire was also three times greater. The use of shields in round

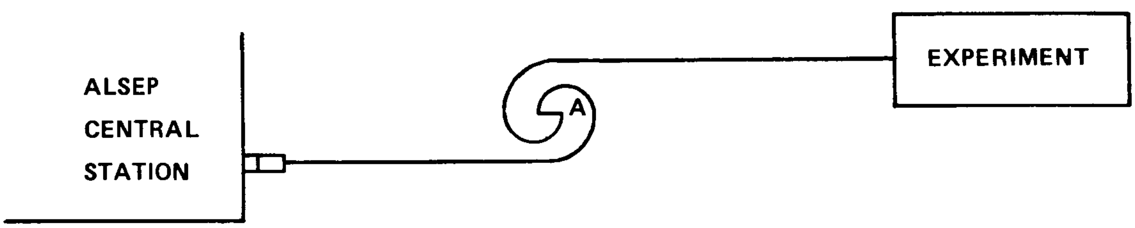
cable causes substantial increases in heat leak from the central station. (An additional 7 watts or 10 percent of total power would be required to hold the same station temperature as achieved with flat cable.)

An additional problem with very long shielded wires is that the distributed capacitance throws substantial additional load on the driver gate (low power) and severely degrades the wave shape. This degradation can cause double triggering.

The principal disadvantage of flat cable at the time that ALSEP was designed was that much less experience was available in manufacture and use of flat cables and their connectors. Special insulators were required to withstand the temperature and narrow conductor widths were necessary to hold the weight and volume advantage for ALSEP. A book could be written about this development program (and, in fact, was in the form of 31 ALSEP TM's and immeasurable other correspondence).

Chosen Design

Stowage and ease of deployment are fundamental to ALSEP. A concept was derived that would allow straight pull to do the job.



A removable winding key was slipped through the side of the cable reel to fork the midpoint of the flat cable. A simple winding motion folded the cable into a counterwound spring format and the key was removed. The other design feature of particular interest to potential users was signal arrangement. Power loss in the cable would require line and return conductors of 200 square mils, but this would be very heavy and inflexible in all signals used the same conductor. Instead, 4×50 square mil conductors were used (0.025 in. wide by 0.002 in. thick). In long flat cables, it was found by study that low power TTL

signals in adjacent wires would far exceed the safe noise margin. All digital signals were rise-time controlled by an RC circuit at the driver and a capacitor at the receiver. Transitions in the uncontrolled low power TTL gates were 30 nanoseconds but 1 to 10 microseconds after rise-time control. Beware of slowing signals too much because double trigger of the receiving gate will occur. If insufficient control is exercised, then crosstalk will be excessive.

Even rise-time control did not provide an adequate margin of safety, therefore digital signal lines were separated by a SIGNAL ground conductor. Since coupling between conductors is almost exclusively capacitive, the ground acts as an electrostatic shield and reduces crosstalk to acceptable levels.

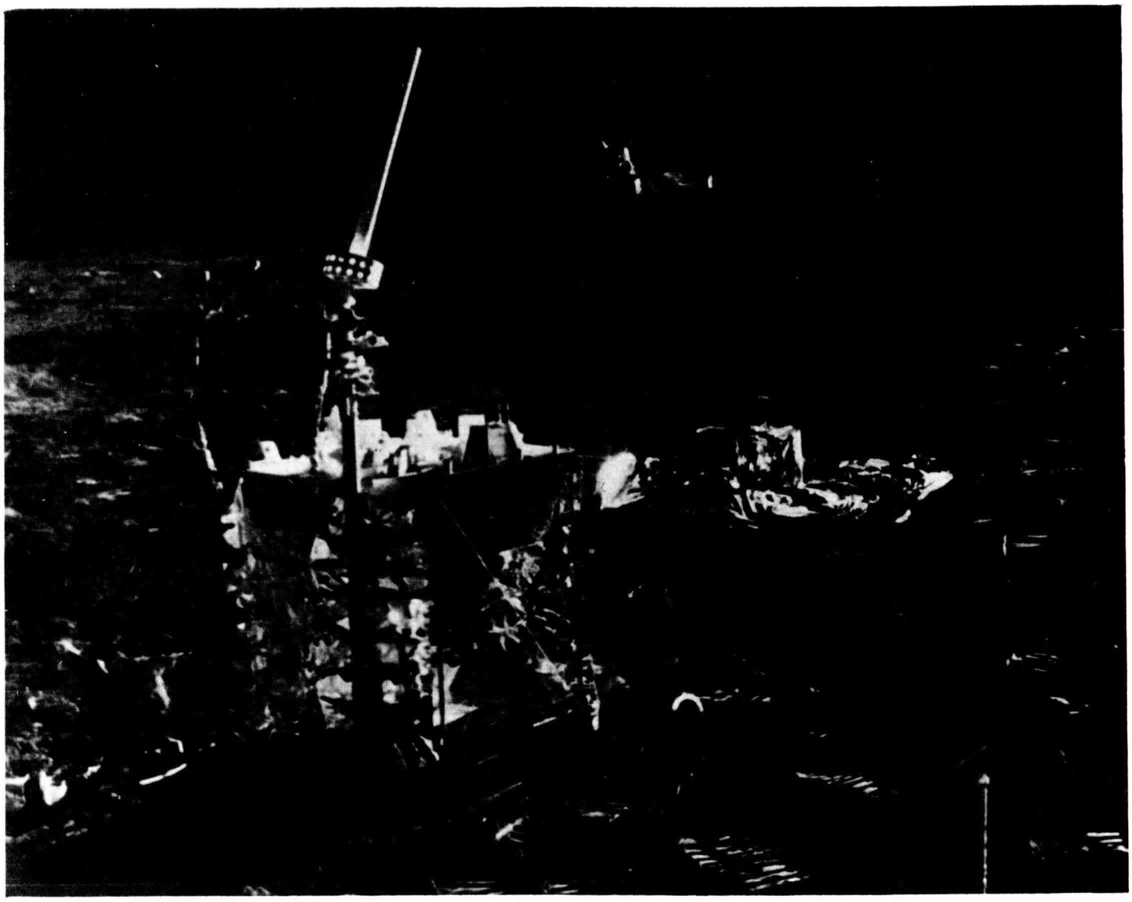
Examples of Development Problems

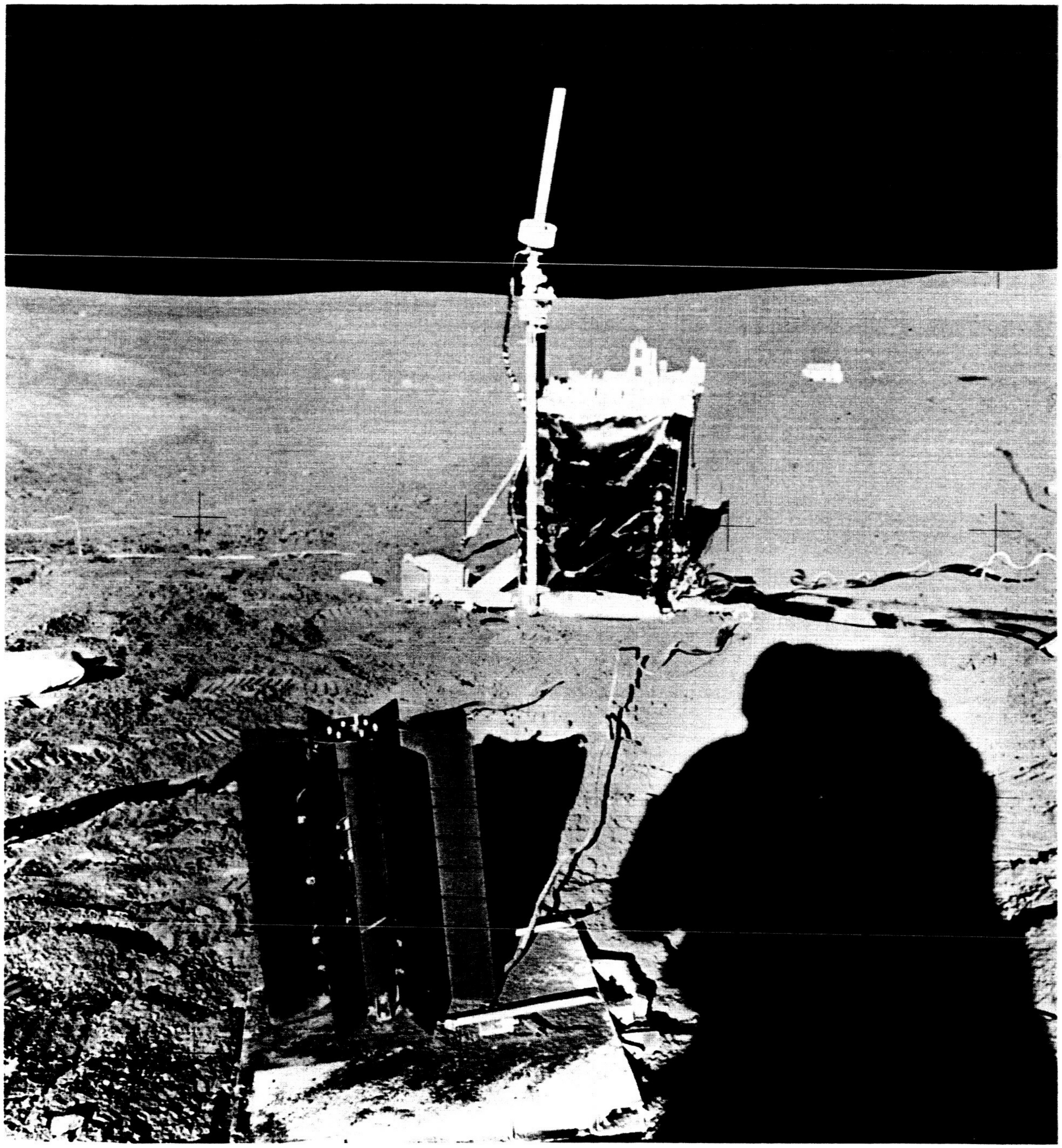
Flat cable in tension has very high strength, probably higher than round-wire but in shear where the stress is concentrated at one edge of the cable then tearing can occur around 35 pounds of pull. MSC and MSFC experts were consulted for solutions to the problem and demonstrated the use of glass tape to reinforce cable edges. With this reinforcement, the cable would withstand 10 times greater dynamic loads.

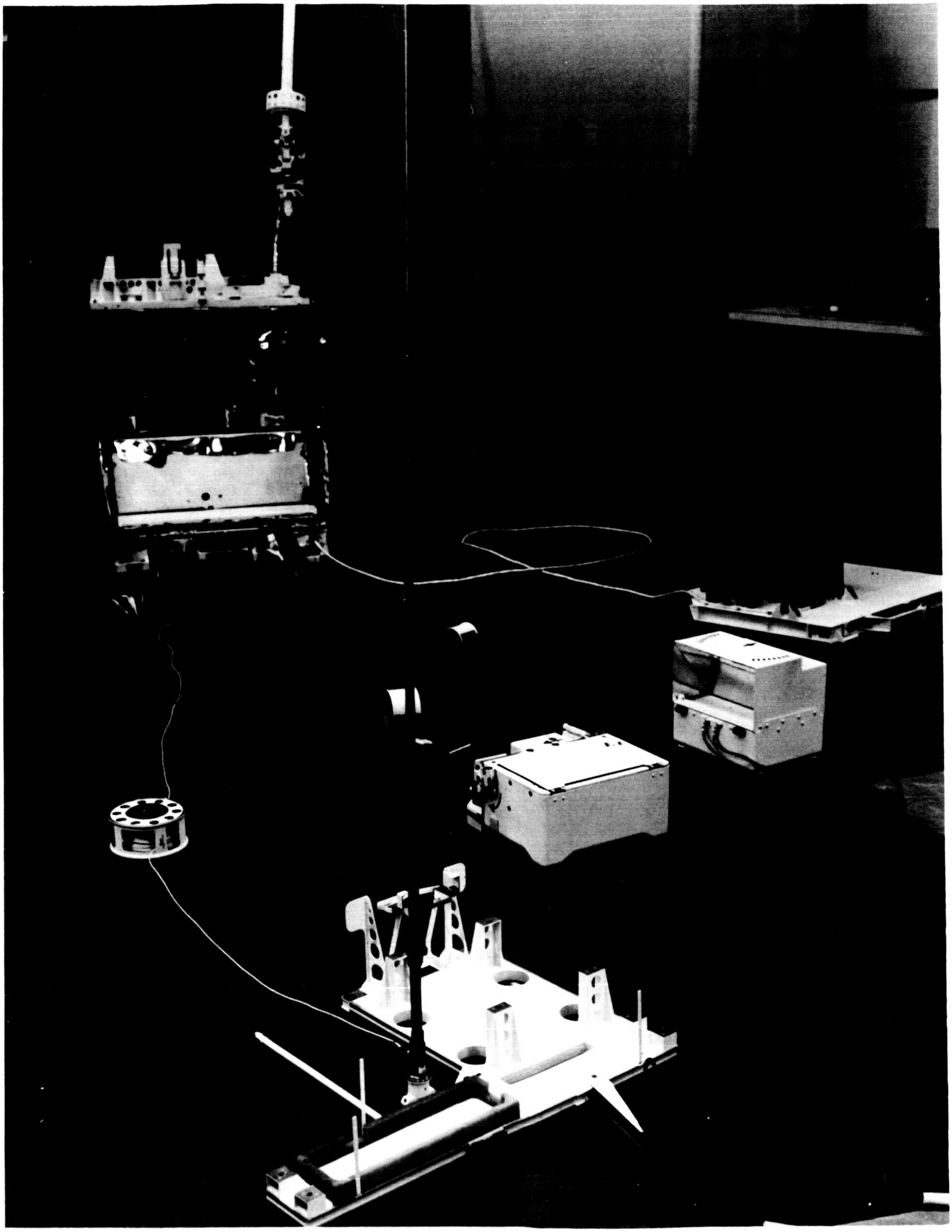
Another interesting feature of flat cable was illustrated by the Lunar Ejecta and Meteorite Experiment which has an electrostatic sensor. When its flat cable was partially stowed, it was noticed that a constant number of false "hits" occurred. When the cable was fully reeled, the "hits" went away. The cause was diagnosed as a grounding problem due to the sensor seeing the case ground which was isolated from signal ground. The signal ground carried return currents and, therefore, a potential difference existed between the case ground which carried no current and the signal reference point. When signal and case grounds were joined, the problem disappeared. A stowed flat cable essentially becomes a noninductive winding. It therefore has much less potential difference than when it is fully deployed.

An example of a development problem was the discovery of short and open circuits in a connector that previously had moderate use. The pins were found to have sharp edges left by the press tool. The edge had scored the PC board gold surface and small slivers of gold had bridged between adjacent pads. The press tool made contacts in "upper" and "lower" pairs which, when placed in the connector shell, contacted alternate sides of the pads. A small displacement of the pad with respect to the pin caused contact to be lost. The

solution was to round the pin in the contact area so that a smooth pressure, rather than a scraping action, occurred. This also took care of the lateral tolerance problem, not only accommodating worst-case tolerance but allowing some margin of safety.







PRE-SUMMARY

1. INTRODUCTION TO ALSEP
2. REQUIREMENTS OF ALSEP FLAT CABLE
3. COMPARISON WITH ROUND CABLE
4. DESIGN FEATURES
5. 3 DESIGN PROBLEMS
6. SUMMARY AND PROGNOSIS

CABLE REQUIREMENTS

WIDE THERMAL RANGE

SIMPLE DEPLOYMENT

LIGHT WEIGHT

SMALL VOLUME

LITTLE "MEMORY"

PERFORMANCE STABILITY

FLAT – ROUND CABLE TRADEOFF SUMMARY

40 CONDUCTORS - 40 FT LONG BASELINE

FEATURE	FLAT *NEEDED WORK	ROUND
THERMAL RANGE	POSSIBLE	POSSIBLE
ABRASION	KAPTON OK	POSSIBLE
MEMORY	LITTLE*	SUBSTANTIAL (NOTE CCIG CASE)
EASE OF DEPLOYMENT	EXCELLENT*	UNACCEPTABLE
WEIGHT OF TOTAL	8 POUNDS	> 25 POUNDS
VOLUME	90 $IN.^3$	250 $IN.^3$
HEAT LEAK	1.5 WATTS	8.5 WATTS
ELECTRICAL PERF LIMITS OF CABLE LENGTH	50 FOOT POSSIBLE*	6 FOOT MAXIMUM LPTTL 35 FOOT MAX FOR MPTTL

DISADVANTAGES OF FLAT CABLE

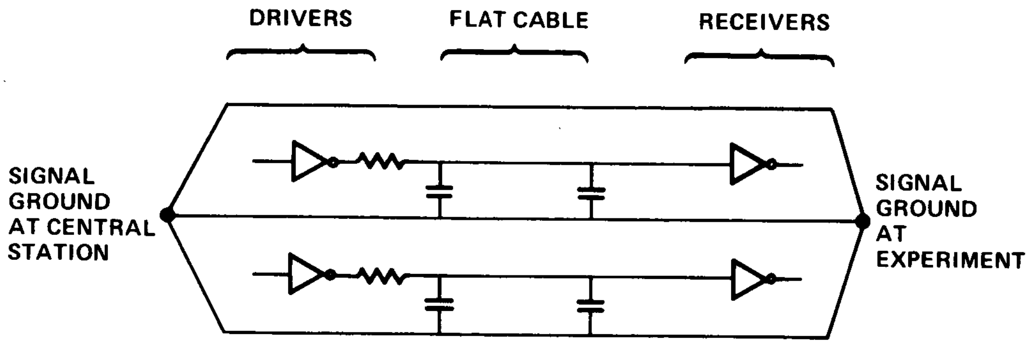
NO PREVIOUS LUNAR EXPERIENCE

AVAILABLE CABLE WAS 0.075 CENTRES

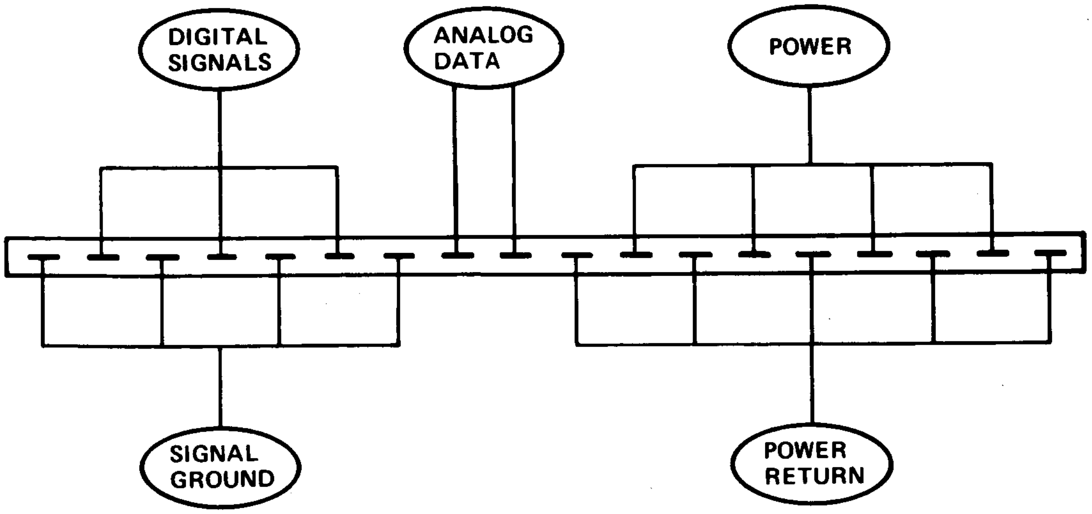
FEW ESTABLISHED STANDARDS

31 STUDIES TOTALING OVER 1000 PAGES

CROSSTALK SUPPRESSION



SIGNAL ARRANGEMENT



CABLE TEARING

HIGH TENSILE STRENGTH

LOW SHEAR STRENGTH

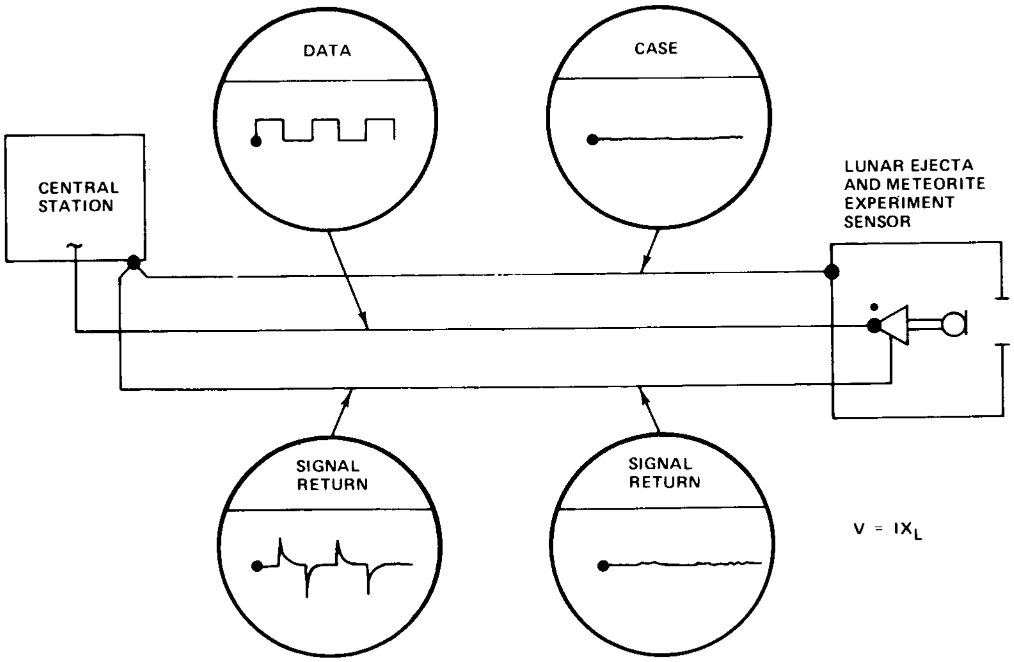
REINFORCE WITH GLASS TAPE

PREVENT STRESS CONCENTRATION

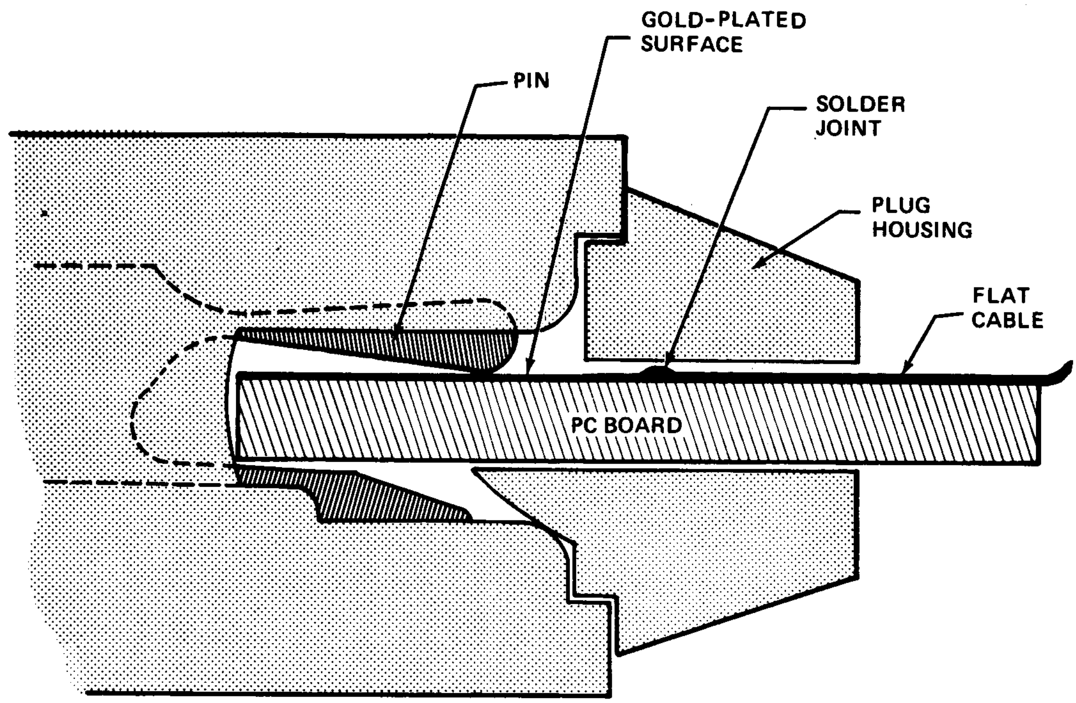
THREE TIMES STRONGER

LITTLE WEIGHT PENALTY

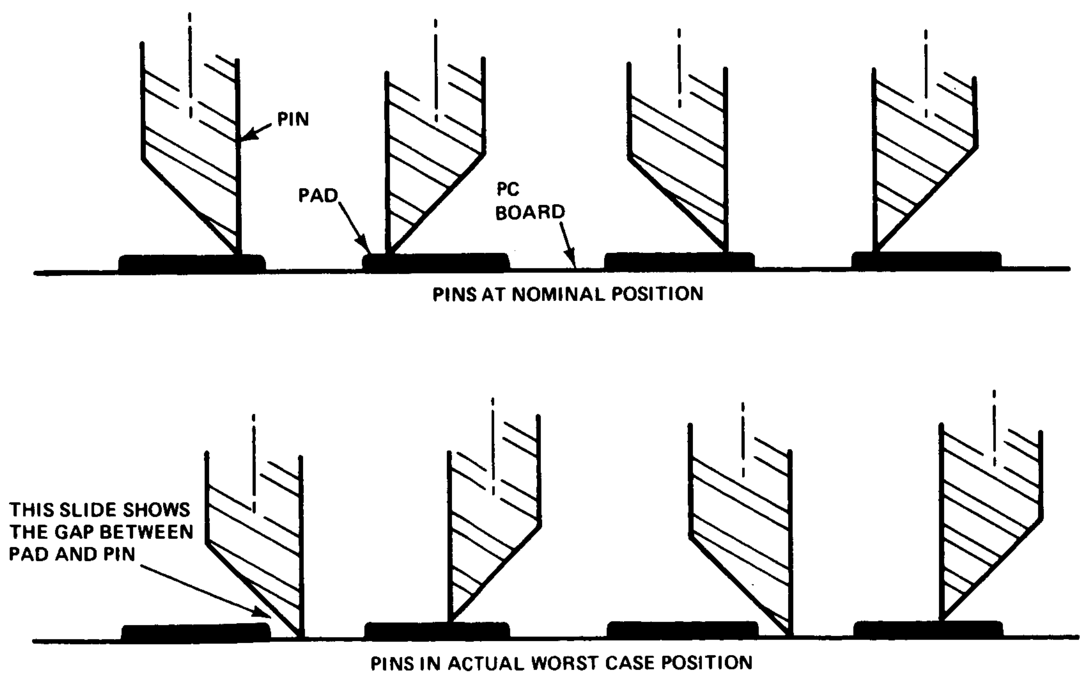
CABLE PERFORMANCE UNSTOWED



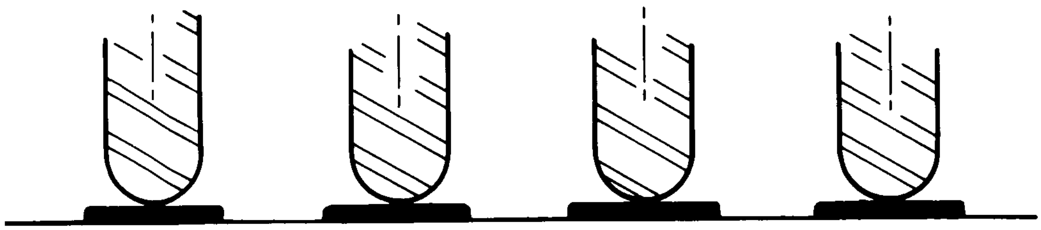
SECTION THROUGH CONNECTOR



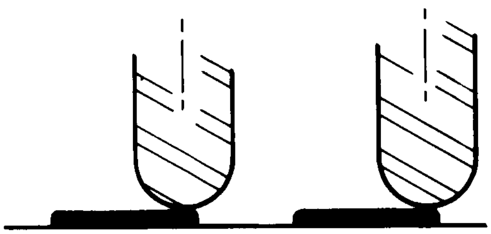
SHARP PIN PROBLEM



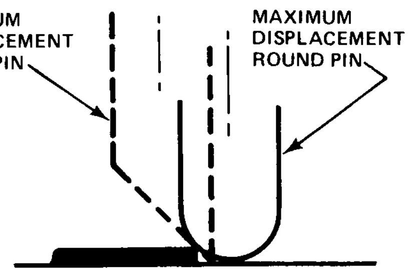
ROUNDED PROFILE



ROUNDED PINS AT NOMINAL POSITION



ROUNDED PIN MORE TOLERANT



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CABLING DESIGN FOR PHASED ARRAYS

By Irving Kruger
RCA

Cabling designs for phased arrays

I. D. Kruger | L. F. Jurkiewicz

The ribbon-cabling system used for the AEGIS phased array provides minimum cable bulk, complete EMI shielding, rugged mechanical design, repeatable electrical characteristics, and ease of assembly and maintenance. The ribbon cables are 0.040-inch thick and come in widths up to 2½ inches. Their terminations are molded connectors that can be grouped in a three-tier arrangement, with cable branching accomplished by a unique matrix-welding technique.

For the AEGIS program, the Missile and Surface Radar Division has produced a phased-array antenna representing the latest state of the production art.

For the array cabling system to keep pace with the required production techniques being advanced in other component areas (*e.g.*, ferrite phase shifters, multilayer distribution boards, strip-line RF power dividers, and dip-brazed horn element clusters) new cabling technology application was necessary. Each array module requires cabling for 32 phase shifters, 38 twisted-pair inputs and 5 DC voltage leads. When the compliment of 140 array modules are considered and phase shifters, monitoring circuits, and shielding circuits are added—some 23,000 individual wires are being distributed throughout the array.

The first attempts were to stay with conventional, individually shielded, twisted-pair leads as a distribution method—the approach used for the experimental subarrays. This technique had the advantage of economy in cable harness manufacture. However, the sheer bulk of the wire and connecting devices and the necessity for completing the thousands of connections reliably during the final assembly operations forced the examination of other techniques.

The bulk of harnesses and connectors, in itself, would not be a valid reason for departing from established approaches, if it were not for the space and access problems associated with production phased arrays. Rear access to all line-replaceable components from within the ship's deckhouse is mandatory for maintenance of the array. The phased array principle causes phase shifters and elements to be spaced on a precise repeated configuration within the confines of a rigid aluminum welded structure. Furthermore, the array modules are individually fed by waveguide, self-duplexing directional couplers that consume a considerable portion of the available space, particularly when disconnect flanges are considered. Yet, driver-board nests and receiver phase shifters must be accessible from within the array, so a clear access space must be left which further reduces the available volume.

Thus, it becomes mandatory to limit cabling harness size to the very minimum and to reduce or eliminate connecting devices and junction boxes.

The requirements for the cable harness system are then reduced to an approach providing:

Minimum cable bulk;
Few or no connectors;
Completely shielded cables and connectors for electromagnetic-interference protection; and
Rugged mechanical design to withstand assembly handling stresses and meet shipboard conditions.

Fortunately, developments in cabling techniques had been going forward during the 1960's, not necessarily for application to phased arrays, but motivated by the requirements listed above for other electronic applications. In military as well as commercial applications, packaging constraints were forcing an increase in the wire-to-harness-volume ratio.

AEGIS cabling approach

The ribbon-cable and integral connector-as-a-junction-box technique selected for the AEGIS phased array provided a cable system meeting the required needs. This approach features

Authors Kruger (seated) and Jurkiewicz.

Irving D. Kruger
Mechanical Design
Missile and Surface Radar Division
Moorestown, New Jersey
received the BSME from Newark College of Engineering in 1940 and the MSME degree from Drexel Institute of Technology in 1959. Mr. Kruger has 31 years engineering and engineering leadership experience at RCA in design, development and manufacturing liaison of antenna structures, pedestals, servos, and electronic equipment essentially as applied to radar systems. Mr. Kruger's recent assignment was design of phased-array assembly for the AEGIS Ship Program. This effort required integration of the thousands of phase shifters, drivers, and horn elements into a welded frame structure for mounting within the ship's deckhouse. He is a licensed professional engineer in New Jersey, a member of AIAA, ASME, Tau Beta Pi, and is an adjunct professor in Machine Design at Drexel Institute of Technology.

Leonard F. Jurkiewicz
Equipment Integration
Missile and Surface Radar Division
Moorestown, New Jersey
received the BSEE from the University of Detroit. He joined RCA in 1950 as a Field Eningeer with the Service Company. After assignments as instructor, leader, and engineering manager in RCA Service Company through 1956, he was an electrical design engineer at M&SR and AED. During this period, he received the MSEE from the University of Pennsylvania. On AEGIS, he has been subsystem integration and design engineer assigned to integration of the phased array and its associated temperature control system. He is a member of Eta Kappa Nu and a holder of an FCC Radiotelephone/Radar License and member of the IEEE.

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conductors of silver-plated-copper strips, 0.003×0.020-inch cross-section on 0.050-inch centers, laminated into a dielectric base and shielded with 0.0015 inch copper foil. The ribbons are machine laminated to close tolerances, are 0.040-inch thick, and come in any desired widths up to 2½ inches. The Army had initiated connector specifications (MIL-E-55544), providing 0.100-inch-thick and 2⅝-inch-wide connector inserts that terminate the ribbons by a special welding process to a unique bend-proof pin-and-socket combination. The molded connector inserts can be grouped into a three-tier arrangement, as further described herein. By this approach, analog signals from one cabling harness source can be combined with digital-logic signals from another harness grouping and DC power from another group at the three-tier shielded receptacle.

The ribbon cable approach also offered an additional unique connecting feature: main-harness to individual-array-module branching could be accomplished using a matrix-welding technique. This process elminated the need for exposing connecting points for wire wrap or solder connections. The matrix welding is performed by a patented "flex weld" process perfected by the Ansley Corporation and licensed for general use to a number of ribbon cable manufactures. The method employs a controlled-energy release to the weld when the applied pressure reaches a prescribed level. The weld tips are preheated and penetrate the dielectric laminate containing the conductor strips so that welding is actually accomplished in an oxidation free environment under the dielectric melt. When completed, the ribbon-cable matrix connections are still protected by the dielectric and outer shield, and an additional potting compound is applied for strain relief. The joint is only four times greater in volume than the original ribbon-cable matrix section.

Electrical characteristics

The ribbon-cable configuration allows closely controlled electrical-transmission-line characteristics to be established and maintained. Conductor spacing can be accurately maintained relative to the shield and adjoining conductors, and the dielectric can be chosen for proper capacitance. Analog and digital signal attenuation in the array must be controlled to insure proper phasing of the drivers.

Table I—Critical signal and cable characteristics.

Analog signal characteristics	
Risetime:	0.75μs
Falltime:	0.75μs
Pulse width:	10μs
Pulse amplitude:	30 levels from 0 to 15 V
Frequency:	5 kHz
Digital signal characteristics	
Risetime:	10 ns
Pulse duration:	3 μs
Pulse amplitude:	0 to 0.25 volts
Electrical characteristics of ribbon cable for analog/digital-signal distribution	
Impedance:	110 ± 15 ohms
Capacitance:	17 ± 3 pF/ft
Propagation delay (analog signals):	1.8 ± 0.1 ns/ft per foot
resistance:	0.1 ohms/ft (± 15%) at 20°C (equivalent #30 wire)
Crosstalk (analog):	15 mV (max.) settled to adjacent pairs
Crosstalk (digital):	15 mV (max.) settled
Shielding:	70 dB attenuation to electric fields and plane waves between 14 kHz and 10 GHz
Branching (analog):	Up to 10 loads, at 10 kilohm/loads
Branching (digital):	Up to 5 loads, at 18 kilohm and 15 pF/load

H. Inacker and L. Henderson of the Signal Processing group at M&SR were able to analyze the system to determine the required ribbon-cable impedance and delay characteristics and prescribe testing procedures. Table I summarizes these signal requirements and lists the electrical characteristics of the cable. Early tests on experimental lengths of the ribbon cable proved that the signals could be properly distributed to the array modules, and the final testing of production cables has also confirmed the design.

Electrical distribtuion

The input and output connections to the phased-array antenna are as shown in Fig. 1. Except for coaxial and waveguide interfaces, signal inputs come through high-density connectors and multiple-pair shielded cables. The discussion that follows mainly concerns the use of ribbon cables with welded junctions for branching of signals from main trunk lines to 140 array modules and 68 receive phaser units. The DC bus distribution throughout the array also imposed several challenges, leading to development of a unique laminated bus which is also described.

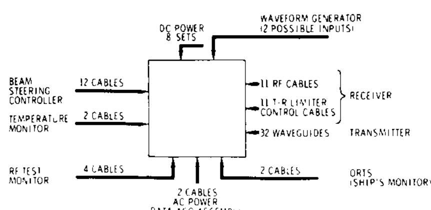


Fig. 1—AEGIS multifunction-array-radar antenna inputs and outputs.

Array modules and receive phaser assemblies

The major electrical distribution problem within the antenna involves routing signals and power through the 141-pin connectors (3 layers) to each of the 140 array modules and through the 51-pin connectors (3 layers) to each of the corresponding receive-phaser assemblies. Fig. 2 shows the relative locations of the array (face) modules within the antenna structure, and Fig. 3 shows the configuration of a basic array module. There is one receive-phaser assembly required for every two array modules. These receive phasers are located behind their respective array modules on the antenna structure. Fig. 4 shows the functional grouping of the array modules, receive phasers, and associated components that make up a single typical subarray.

RF subarray

The array module can be thought of as the basic distribution unit for control signals. However, for RF purposes, the array module is part of a subarray: two array modules are combined for receive-only operation and four array modules are combined for transmit-only. One receive phaser assembly is associated with each two array modules as shown in Fig. 4.

Array-module inputs

Phasers (coarse phase shifters) at the array-module face shift the phase of incoming or outgoing RF energy. This phase shift determines the antenna directivity (coarse steering). The inputs to the array module needed to achieve coarse steering are defined in Table II.

Since the array modules are identical, a problem arose when the modules had to be installed in normal and inverted positions. If all modules shared the same signals, phaser signal locations

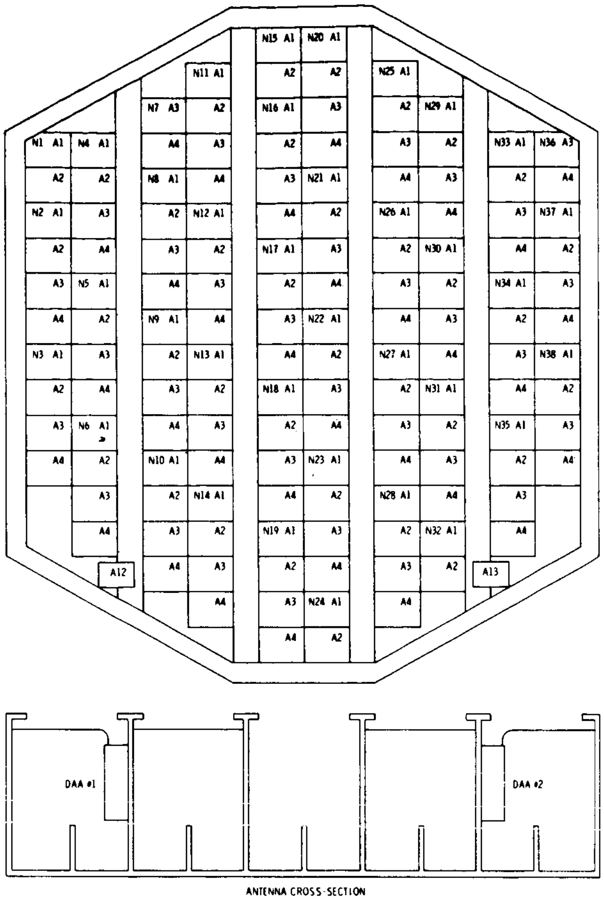


Fig. 2—Layout of array modules on AEGIS phased-array antenna (view from inside the ship's deckhouse).

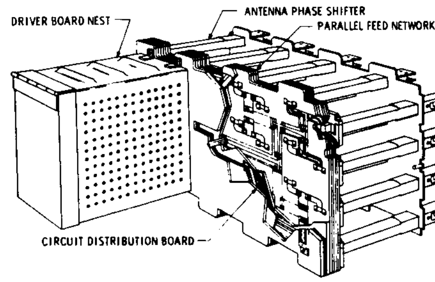


Fig. 3—Typical element array module.

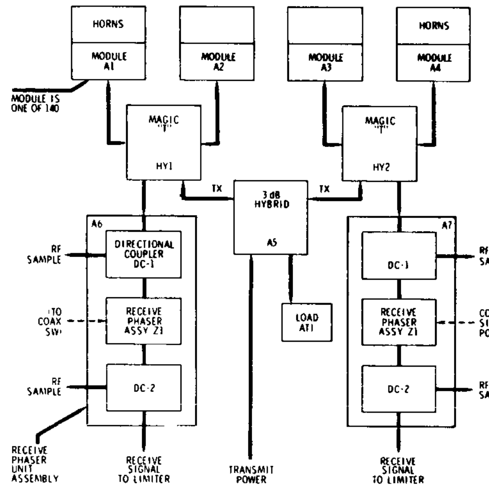


Fig. 4—Typical grouping of RF subarray modules.

would thus be transposed in an inverted module. This problem was overcome by reversing ribbon inputs and pairs to P1A and P1B of each inverted module (see Fig. 5). A staggered (or jagged) weld-takeoff pattern was required, and care had to be exerted that signal and signal-return lines were not reversed.

Table II—Array module inputs.

Quantity	Type
32	Analog (pair)
5	Digital (pair)
	• Start gate A
	• Start gate B
	• Clamp gate
	• Reset
	• Driver test strobe
1	Monitor, status (pair)
1	Spare (pair)
5	DC power lines
	± 12 VDC and returns
	± 38 VDC and returns

Notes
1) No more than ten modules get branched analog signals from any one pair of main trunk lines.
2) No more than five modules get branched digital signals from any one pair of main trunk lines.

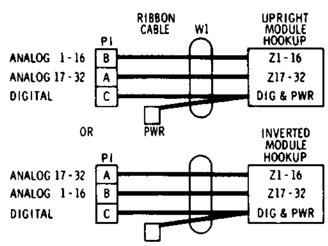
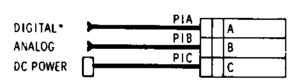


Fig. 5—Array module inputs.

Receive phaser inputs

For every two array modules, one receive phaser assembly is used, as shown in Fig. 4. One phase shifter and one circuit board are the main components of the receive phaser.

The receive phasers provide fine steering; Table III shows the required inputs. A problem arose when it was desired to use the same part number in various locations where the direction of RF was reversed. This was solved by reversing the gates A and B in the ribbon cabling distribution (see Fig. 6)



* GATE A AND B ARE REVERSED IN INVERTED UNITS

Fig. 6—Receive phaser inputs.

Table III—Receive phaser inputs.

Quantity	Type
1	Analog (pair)
5	Digital (pair)
	• Start gate A
	• Start gate B
	• Clamp gate
	• Reset
	• Driver test strobe
1	Monitor, status (pair)
1	Spare (pair)
5	DC power lines
	± 12 VDC and returns
	± 38 VDC and returns

Notes
Analog signals are not shared between units, but Digital signals are shared by as many as five units.

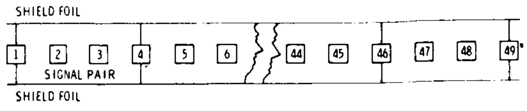


Fig. 7—Analog ribbon cable cross-section.

Analog signals cable

A cross-section of the analog signal ribbon cable (Fig. 7) shows the 49 rectangular conductors and the 0.0015-inch copper foil shield above and below the wires. The shield is tied to the end wires, feeding a 47-pin array module connector wafer.

The conductors are divided into signal pairs, each separated from its neighboring pair by a conductor grounded to the shield system. In general, the grounding is done only at the antenna entry point.

Digital signals cable

A cross-section of the digital signal ribbon cable (Fig. 8) shows the 23 rectangular conductors and the 0.0015-inch copper foil shield above and below. The shield is tied to the end wires.

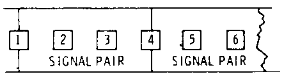


Fig. 8—Digital ribbon cable cross-section.

The conductors are divided into signal pairs. Each pair is separated from its neighboring pair by a conductor grounded to the shield system. Cable shield grounding is done only at the antenna entry point and at the module.

DC power bus

Each array module requires the following DC power:

38-V at 1.1-A average current (7.1-A peak)
+12V at 1-A
-12V at 0.43A

These voltages are provided via laminated low-impedance bus-bar sections, which are made up of +38 V, 38 V return, +12 V, -12 V, and +12 V and -12 V return lines in the forms of ribbons in each encapsulated section (see Fig. 9).

To minimize bus size, but most of all to favor reliability in the event of bus failure, the antenna is divided into eight groups of DC power feeds. Four group inputs enter the left side of the antenna and the other four inputs are at the right side. Each group has capacity of 38 V at 30 A, +12 V at 20 A, and -12 V at 10 A. The problem here was how to keep the +38-V line drop below 0.8 V, even under the pulsed load. Less stringent voltage drop of 2% on the 12-V line was more easily met.

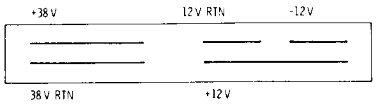


Fig. 9—Typical power bus section.

The power bus shown in Fig. 9 consists of conductive copper strips of cross-section area required to meet voltage drop requirements at specified current characteristic. Thin insulation provides isolation between layers but permits maximum capacitance and minimum inductance. A tight moisture seal is obtained by potting the stack of layers.

Screw terminals on each bus section conveniently allow interconnection of bus sections and power takeoff to modules.

Overload current stresses that could result in bus failures were minimized by limiting the output current of the power supply and fusing the loads. The bus was so designed that short-circuit currents available would not cause damage to the bus.

Simulated electrtrical tests

To verify that cable characteristics were adequate, tests were performed on simulated cables between the antenna and the beam-steering controller, and on cabling within the beam steering controller.

The tests demonstrated that line reflections are well within allowable limits, risetimes and falltimes required can be supported by the transmission lines, and crosstalk limits of 15 mV were not exceeded. Signal integrity was maintained with common mode levels of 2 volts.

Cable installation and selection

From the antenna structure wall to the outside of the receive waveguide. and duplexers, a distance of 4 inches is allowed so that free access can be maintained to the driver cards. This then allows an average space of approximately ¼ inch for cabling along the wall for the digital cabling and DC bus and a relatively small additional space for the distribution junction (MIL Connector) close to the receiver phase shifters.

Also the digital cable junctions must be as close to the array module distribution board as possible to comply with electrical-transmission-line-effects requirements. This made it mandatory to locate the distribution junction close to the position indicated. The junction system is shown in Fig. 10. Note the analog signals emerging from the matrix junctions on the rear of array, being grouped with digital signals from the internal vertical run, and the DC bus straps from the main bus on the rear inside flanges. The cabling is collected

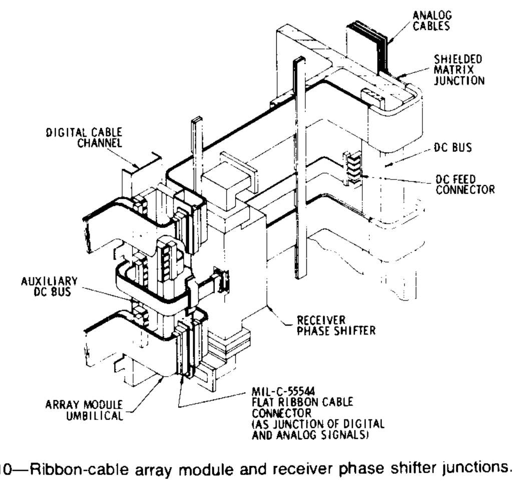


Fig. 10—Ribbon-cable array module and receiver phase shifter junctions.

Table IV—Cable system tradeoff study.

Characteristic	Conventional Shielded Twisted Pair	Twisted Pair in Ribbon Belt	Shielded ribbon cable
Cable volume (in.^{3})	6300	5100	3500
Connector volume (in.^{3})	3500	2900	2200
Separate branching (in.^{3}) device volume	6100 (wire wrap)	6100 (wire wrap)	700 (flex-welded matrix)
Shielding effectiveness	Braided shielding terminated at connector.	Braided overlay terminated at connector.	Copper foil terminated at connector.
	Branching requires a separate shielded junction housing.	Branching requires a separate shielded junction housing.	No separate housing required since shield is continuous at Matrix.
Relative final array assembly time	3	3	1
Reliability comparison	Use of wire wrap or soldered.	Use of wire wrap or soldered.	Welded.
	Branching not as reliable as welded.	Branching not as reliable as welded junction.	Termination at branches & connectors.
Relative cost	2	3	4

in the three-tier wafer/receptable or "connector as a junction box" in the manner shown. The final objective of conveying the signals and power to the array module distribution board is accomplished by means of the umbilical 3-tier cable run which must be positioned along the channel wall. The array module umbilical cable, in particular, must be constructed with a minimum of volume since severe space restrictions exist at the point of connection of the "magic tees" to the array module, considering allowance of room for disconnect flanges and for the cooling baffle system in this area.

The overall design also requires that the complete array module must be removable for major overhaul, without disturbing the main cable system. The minimal size umbilical emerging from the single connector, as indicated, accomplishes this objective.

The approach of obtaining more volume by movement of the column walls, or "flaring" of the structure could not be considered because of the prohibitive weight increase for the structure, and the prohibitive size and weight increase for the ship's deckhouse. In any event, the front distribution of the umbilical runs must be maintained within the volume as allotted, to comply with the basic array principle of maintaining the element phase shifters on a prescribed, repeated grid for phased-array RF operation.

All of these restraints served to establish the criteria for the choice of cable technique. The effort involved constructing layouts with the minimal cable volume necessary to contain the various systems and to ascertain if the approach could be accommodated within the space. The requirement for shielding was also prevalent throughout all of this effort. That is, adding to the bulk of cable and junction box or connector problem was the necessity to carry a completely shielded and grounded system from the input of the array to the array module distribution board and drivers.

The overall results of the cable tradeoff study are as indicated in Table IV. For the array module umbilical cable, the comparative space consumed by conventional twisted-pair versus shielded ribbon-cable is shown in Fig. 11. Also indicated are the comparative sizes of the connectors. The twisted-pair cable could not be used in this application in the position shown since the cable must not block the air intake to the driver-card nest. Placing such a cable along the structure wall would not be possible considering the access requirements to the input waveguide connection indicated, and the problem of providing an air baffle in this area. The ribbon cable consumes a minimum of volume and satisfies the access requirement as well as allowing removal of the array module for servicing.

Ribbon-cable fabrication

The present state of art in the manufacture of ribbon cables offers a wide variety of configurations and materials, available from a number of manufacturers.

The cable has a high flexibility and would provide long life in applications where chassis removal or other motion is required. For the AEGIS phased-array antenna, the cable remains fixed except for the instance where the array modules are installed or removed, and this amount of flexing is negligible. The cable is highly reliable in comparison with bundled wires. The shield provides improved cut-through and abrasion resistance. All conductors are of the same length, which causes all conductors to share equal stresses, providing higher mechanical strength than round wires. Conductor size is thus reduced to electrical requirements needs and not mechanical requirements.

Assembly time is speeded using the flat-ribbon configuration since the cable is completely preformed to a relatively precise mechanical shape conforming to the structure. The cable electrical characteristics of impedance, capacitance, and inductance are repeatable within close limits for succeeding assemblies, thus reducing their effect on radar performance.

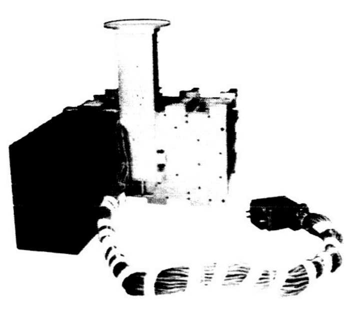


Fig. 11—Comparison of space consumed using twisted-pair cabling (left) and ribbon cabling (right).

For AEGIS, the dielectric supporting the conductors is FEP teflon providing toughness and high temperature resistance for manufacturing operations, potting etc. This material provides means for heat sealing the laminate to the outer copper shield. The teflon, though opaque in thick layers, is still sufficiently transparent to allow the welding junction to be viewed through the optical positioning head when forming matrix welds.

The conductors are silver plated to aid conductivity but also to provide a means for improving the bond strength of matrix welds, and welds to the connecting pins. The silver melts, forming a brazed junction fillet at the weld point under the application of the flex weld process which markedly increases strength of the junction.

The major steps in the manufacture of the ribbon cable are illustrated by Figs. 12 through 17.

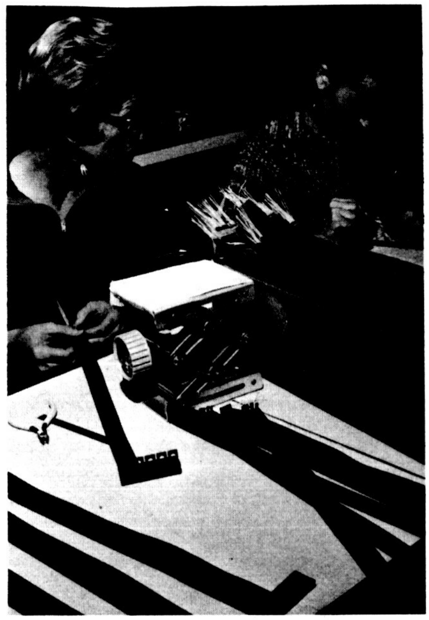


Fig. 12—Typical operation in preparation of ribbon cable for mating with the connecting wafer. Shown is a DC power conductor, with the ribbon being connected by weld terminations to a number of parallel wires which will in turn be welded to the connecting pins.

Fig. 13—The normal connection to the wafer and pins is made directly to the laminated ribbon strips using the flex-weld process. In this photo, the operator is viewing the weld junction under the scope for centering. The weld tips are heated and forced through the teflon dielectric which is melted at the junction. Pressure is applied and when the proper joint resistance is obtained, the weld energy is released forming the junction.

Cable assembly

The assembly of the ribbon cables to the antenna is illustrated by Fig. 18, 19, and 20. The assembly shown in Fig. 19 and 20 is repeated on each of the four main vertical flanges of the structure (see Fig. 18). Figs. 19 and 20 also show the digital-cable run under the internal vertical channel, with branches emerging at each array module position to merge with the analog cables at the 3-tier connector. The matrix junctions, with the strain-relief potting, are shown on the rear flange.

The DC bus connection strap is also shown emerging from the rear main bus run to an auxilliary short bus feeding two array-module connectors and the receive phase shifter. As indicated, the receive phase shifter is fed with a ribbon cable of one inch in width terminating in a one inch shielded (MIL-E-55544) connector.

The junction assembly area is located in a relatively small free space behind the driver nest baffle and the vertical receive beam-former. The small volume consumed by the ribbon cable and the flat connectors used made the assembly possible without increasing the depth of structure with attendent increase in weight, deckhouse size, and cable length.

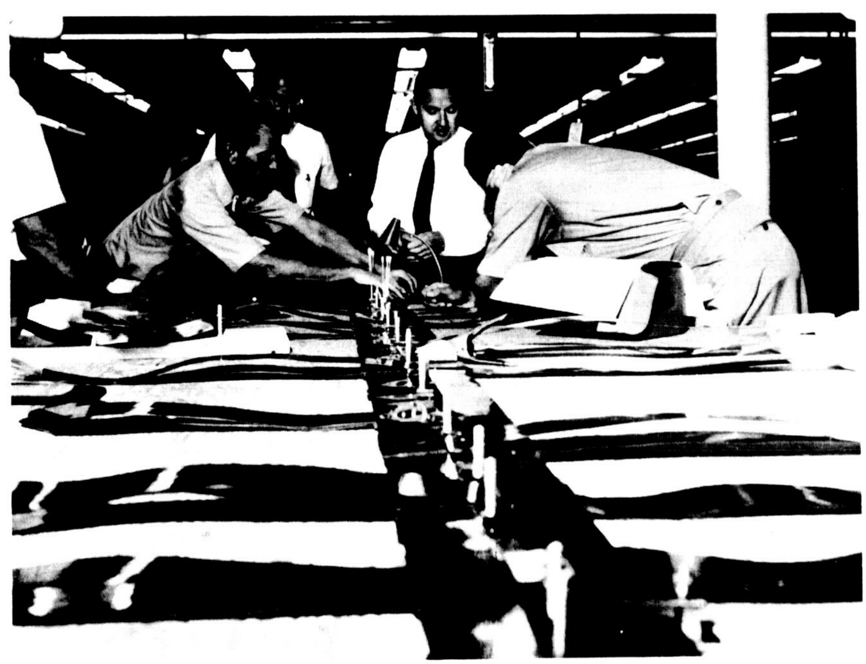


Fig. 17—The completed assembly being readied for shipment. The cable is placed on a plywood board and secured against travel stresses as indicated. The board holds the cable in position for a direct transfer to the rear flanges of the array, with consequent saving in assembly line.

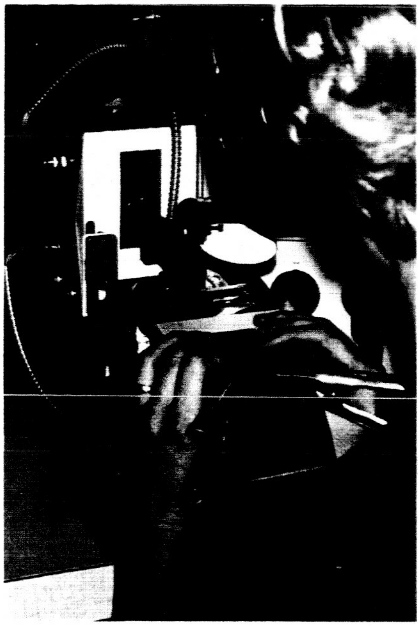


Fig. 14—Another view of the welding process. Here connection is being made to one of the 2½-inch wafer/pin combinations. The wafer has built-in provision for accepting the laminated conductor strips and positioning these under the connecting pins while maintaining all conductors on the 0.05-pitch. Welding is performed through a slot in the wafer which is sealed with an epoxy potting compound after the welding operation.

Fig. 15—The matrix-welding operation showing the ribbon cable with the outer shield stripped back and the weld junctions being performed by the flex-weld process. All junctions are later visually and electrically inspected, with 100% of all weld junctions coming under scrutiny.

Fig. 16—The outer shield being placed back in position with a hand-soldering operation being performed to form a continuous shielded junction. The cable is positioned in the tool as shown and is immediately passed through the potting operation to form a final matrix junction with strain relief provisions.

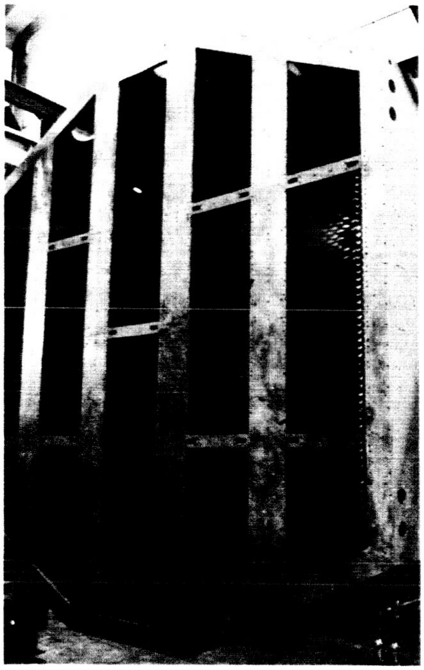


Fig. 18—The structure ready for assembly. Note the four main vertical flanges of the antenna structure.

Fig. 19—Emplacement of the analog cables on the rear flange of one column. The assembly shown is repeated on each of the four main vertical flanges.

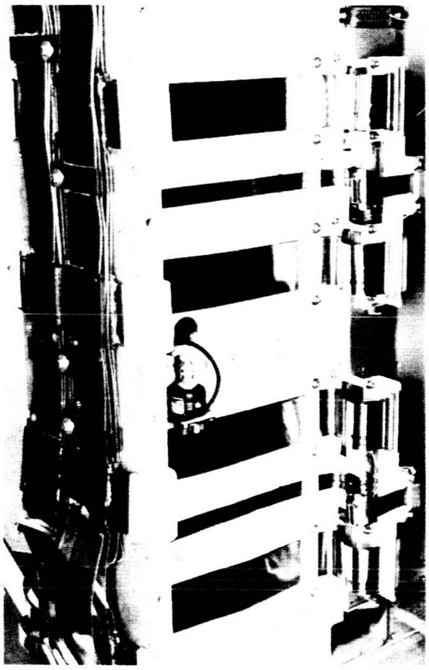


Fig. 20—Close-up view of the junction area where connection to the array module is made. The assembly shown is repeated on each of the four main vertical flanges.

FCC IN VIKING ARTICULATED BOOM

By E. S. Hawkins
Celesco Industries

FCC IN THE VIKING ARTICULATED BOOM

E. S. Hawkins
CELESCO Industries
Costa Mesa, California

ABSTRACT

The application requirements and manufacturing techniques for the flat conductor cable used in the Viking Lander Articulated Boom Unit are described. The Viking Boom is a 3-axis device utilized to position a soil sampler and provide digging forces. This application imposed severe restrictions on size, weight, materials, and choice of manufacturing processes. The final cable assembly design resulted in a combination of collated cable and flexible circuits assembled by resistance welding techniques.

6 October 1972

FCC IN THE VIKING ARTICULATED BOOM

E. S. Hawkins
CELESCO Industries
Costa Mesa, California

INTRODUCTION

The Viking Project will soft-land an unmanned scientific laboratory on the surface of Mars in 1976. The lander will conduct biological and organic analyses of Martian soil on the surface, obtain geophysical and meteorological data and take panoramic color pictures of its surroundings. These investigations are designed to determine whether life on Mars did exist, is present now, or could develop in the future.

The articulated boom assembly shown in Figure 1 in the retracted position is utilized to position the soil sampler, provide the digging forces necessary to scoop up Martian soil, and deliver the soil sample to the biology instrument.

ELECTRICAL INTERCONNECT REQUIREMENTS

The articulated boom contains three 28 vdc bidirectional permanent magnet motors to drive the azimuth, elevation and extend/retract mechanisms. Three dual element linear potentiometers and four single pole double throw limit switches provide position data to the control electronics.

The soil sampler on the tip of the boom assembly contains one dc bidirectional motor, a dc solenoid, limit switches and temperature sensors.

Eight 22 AWG conductors are utilized for the motor, solenoid and temperature sensors and ten 26 AWG conductors are utilized for the limit switches. Total circuit resistance was a major consideration in the choice of AWG sizes.

MECHANICAL DESIGN CONSTRAINTS

The electrical interconnect assembly must be designed for +75°, -225° rotation from the azimuth axis reference point, +45° to -50° rotation from the elevation reference point and 120 inches extension from the fully retracted to fully extended position. The location of these axes of motion on the interconnect assembly is shown in Figure 2.

The boom cross-section when extended is a bi-sinusoidal form as shown in Figure 3. When the boom is wound on the drum the shape collapses into a thin sandwich of metal foil with the cable in the center as shown in Figure 4. The groove for the cable is chemically milled into two pieces of foil, which are then welded together and heat treated to form the bi-sinusoidal shape. When collapsed on the drum, sheer stresses on the weld are developed by the difference in circumference of the upper and lower foil. The 8 mil max thickness for the cable is, therefore, a compromise between excessive stress levels for the boom and an excessively fragile cable.

Since the width of the cable "slot" varies as the boom is retracted, the cable must be centered and held under tension by clamps at both ends. The differences between the coefficient of expansion of the foil and the cable materials and the possibility that the cable will elongate after being held in tension for long periods of time requires a spring-loaded service loop at one end.

The retracted boom is stowed on a six-inch diameter hollow drum which rotates about a 1-1/4 inch diameter stationary hub. The drum rotates approximately seven revolutions for full boom extension. The length of service loop required inside the drum is 3.5 times the circumference of the stationary hub plus an allowance for transition from the drum exit to the hub entry slots. When the boom is fully retracted the service loop is wound around the hub 3.5 turns in the counterclockwise direction as shown in Figure 5. As the boom is extended, the service loop unwinds. At the midpoint, the service loop is loosely folded in the space between the hub and drum. When the boom is extended beyond the midpoint, the service loop is wound clockwise around the hub. Cable clamps are provided at both the drum exit and hub entry slots to limit the cable bend radius to 3/16 inch.

The boom assembly azimuth axis structure rotates concentrically about a pedestal to which the input connector is attached. The elevation axis structure containing the extend/retract mechanism is pivoted on the azimuth structure. Because of the small diameter passageways available for the interconnect assembly in the pedestal and azimuth axis structures, a stranded wire harness was utilized for this portion of the interconnect. A connector assembly for transition from stranded wire to flat cable was mounted on the elevation axis structure. Special harness fabrication techniques were utilized to minimize the twisting and bending stresses imparted to the harness by the azimuth and elevation axes rotation.

SHIELDING REQUIREMENTS

The azimuth, elevation, and extend/retract mechanisms are isolated from the mounting pedestal by gears and bearing. Because structural elements cannot be bonded, conductors must be utilized to provide a low resistance path from each element to ground. Although the boom can be utilized as an overall electrostatic shield around the flat cable assembly, precautions must still be taken to prevent interference between signals. This was accomplished by physically isolating susceptible circuits from noise generating circuits and by providing shields between conductors.

ENVIRONMENTAL REQUIREMENTS

The environmental design requirements for post-landed operations of the boom assembly on the surface of Mars are given in Table 1. The low temperature requirement of -195°F imposes the most severe restriction on the choice of materials and processes for the flat cable assembly.

Table 1. Environmental Requirements
Post-Landed Operations

Temperature — +145°F to -195°F	
Pyrotechnic Shock Response Spectrum —	3000g Peak at 2000 Hz, three axes, both directions
Atmosphere — CO_2 with 18% argon at 15.2 to 2.1 torr	
Dust — (1 - 10 micron) 1.43×10^{-10} gm/cm^3 at 70 meters/sec.	
Sand — (10 - 1000 micron) 2×10^{-10} to 8.3×10^{-8} gm/cm^3 at 70 meters/sec.	
Life — (a) 90 days (operational) (b) 350 cycles (qualification)	

In addition to Table 1 environments, the boom assembly must survive typical storage environments for up to 36 months, functional and prelaunch testing environments for up to 20 months, typical launch environments, interplanetary cruise environments for 12 months, Mars orbit environments for 2 months and terminal descent and landing environments. Although, generally speaking, these conditions are not as severe as the post-landed operation environments, the exposure times demand that very stable materials and processes be utilized.

PROGRAM CONSTRAINTS

To ensure that Mars will not be contaminated by Earth micro-organisms, the entire lander will be sterilized by heating after sealing in its capsule. For qualification purposes, the boom assembly including the FCC must meet all functional requirements after exposure to +288°F for 320 hours.

All parts and materials utilized in the FCC must be from an approved list or pass extensive qualification tests. The FCC design must minimize use of organic materials, except pure fluorocarbon compounds.

Traceability records must be maintained for each part and material. Chemical fingerprinting (material identification) is required for each batch or lot of material.

Manufacturing processes require Viking Project approval. Special considerations are required to control organic/biological contamination, general cleanliness and heat compatibility/thermal vacuum requirements.

DETAILED DESIGN CONSIDERATIONS

An overall plan view of the FCC cable is shown in Figure 6.

The choice of materials for the FCC was restricted to those which retain stable characteristics under high temperature/space vacuum conditions and the need for high tensile strength and good flexibility over a wide temperature range. The basic materials chosen were annealed oxygen-free copper, polyimide (Kapton) and fluorinated ethylene propylene (FEP Teflon). Use of electrodeposited copper, epoxy base adhesives, silicone rubber compounds, polyester, polyvinyl chloride, and polyethylene were ruled out by the above considerations.

A polyurethane conformal coating compound (Solithane 113) and an aluminum filled epoxy-phenolic adhesive on a glass fabric carrier were found to be suitable for special applications.

The choice of FCC manufacturing technique was determined by suitability to the length involved and the stringent quality control requirement. Concurrent attempts to manufacture prototypes of the FCC by etch/laminate and collation techniques clearly demonstrated the superiority of the latter for this application.

The choice of connectors was determined by available Viking qualified types and mechanical design constraints. Since connectors suitable for direct termination of the collated cable were not available, alternate methods for adapting the cable to available connectors had to be selected.

Prototype cables were constructed using several approaches. In the first approach round stranded wire was welded to the FCC. The welded area was potted with Stycast 1090 epoxy on one cable and with polyurethane (Solithane 113) on a second cable. Neither of these compounds satisfactorily protected the welded area from handling and boom operating stresses. In the second approach, etched flexible circuits were welded to the FCC cable and three methods for covering the welded area were evaluated. Method one using an epoxy-phenolic adhesive to cement a polyimide film over the welded area was discarded because the aluminum filling deteriorated the insulation resistance between conductors. The second method using Solithane 113 to cement an FEP film over the welded area was discarded because the peel strength was marginally acceptable. The method found to be satisfactory in all respects and shown in Figure 7 used FEP to melt-bond a polyimide strip over the welded area.

COLLATED CABLE DESIGN, FABRICATION, TEST AND EVALUATION

The collated cable configuration is shown in Figure 8. The maximum weight is 21.0 grams/foot. The maximum conductor resistance is 17.8 milliohms/foot for the .167 conductors and 45.0 milliohm/foot for the .063 conductors.

The conductor layout was influenced by the following considerations:

(a) The 0.167 conductor pairs used for motor/solenoid control are physically separated from the 0.167 conductor pairs used for temperature sensor connections.

(b) The three widely spaced conductors on the right side could be used either for grounds or connections to limit switches located on the drum.

(c) The main part of the cable (after slitting away the three conductors) must be straight enough (0.5 inch maximum deviation over a 130-inch length) to fit inside the boom slot. This requires an equal amount of copper on each side of the centerline to equalize stresses.

Special cleanliness requirements imposed on the fabricator were as follows:

(a) Conductor and insulation materials must be cleaned with Freon TF or Dowclene WR.

(b) Materials must be protected against contamination during storage, handling and fabrication.

(c) Fabrication facilities must minimize exposure to contamination.

The following tests and inspections were made per MIL-C-55543 on 100% of the cable:

(a) Conductor resistance

(b) Insulation resistance (500 megohms min)

(c) Dielectric withstanding voltage (1500 vdc)

(d) Insulation flaws (1500 vdc)

(e) Dimensions, weight, workmanship

An evaluation of peel strength, heat compatibility and flexibility was conducted on samples of collated cable with the following results:

(a) Peel strength (1.0 to 3.4 lbs. per inch)

(b) Heat compatibility - exposure to 96 hours at 300°F caused small color changes and slight degradation in peel strength

(c) Flexibility at -195°F - (sample cable was subjected to 50 extend/retract cycles at -195°F with no failure)

ETCHED FLEXIBLE CIRCUITS

The etched circuit at the boom tip is a single layer laminate using 3 oz. annealed copper. Folding techniques at the connector were avoided by using only the outer row of pins for circuit termination. The connector pin termination area is left bare during covercoat lamination and then solder coated. The conductor areas where welds are to be made are bared during fabrication to avoid an insulation stripping operation.

Three separate layers of etched circuits are utilized at the hub end of the cable to bring all of the conductors through the 1.0 inch inner diameter of the hub. These circuits are similar to that at the boom tip except two of the circuits have a 1 oz. solid copper shield on one side.

CABLE ASSEMBLY

The completed FCC assembly is shown in Figure 9. After cutting the collated cable to proper lengths, the portion containing the three widely spaced conductors is slit to the proper dimensions. The termination of the cut is protected from tearing by bonding a strip of Kapton F on both sides of the cable. The three conductor section is folded with two right angle bends and cut to proper length. Additional slits and folding are utilized at the end of the three conductor section to permit attachment of a single terminal lug. After removal of insulation from the conductors at both ends of the cable, the flat cable is resistance welded to the etched circuit terminations. A copper-to-copper weld schedule is utilized with two welds on the wider conductors for added strength. After the polyimide/FEP cover coat is laminated on both sides of the welded area, the connectors are attached by soldering. A conformal coating of polyurethane is applied over the soldered areas.

The brackets made from stainless steel are bonded to the polyimide surface of the cable using an epoxy-phenolic adhesive.

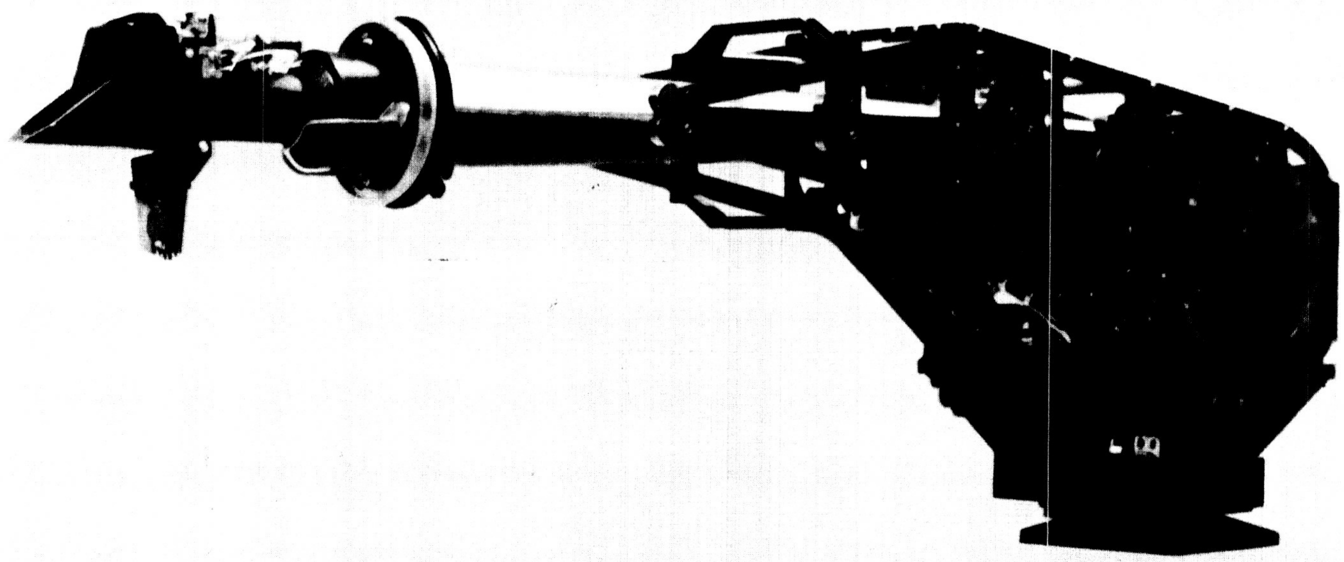


Figure 1. Boom Assembly in Retracted Position

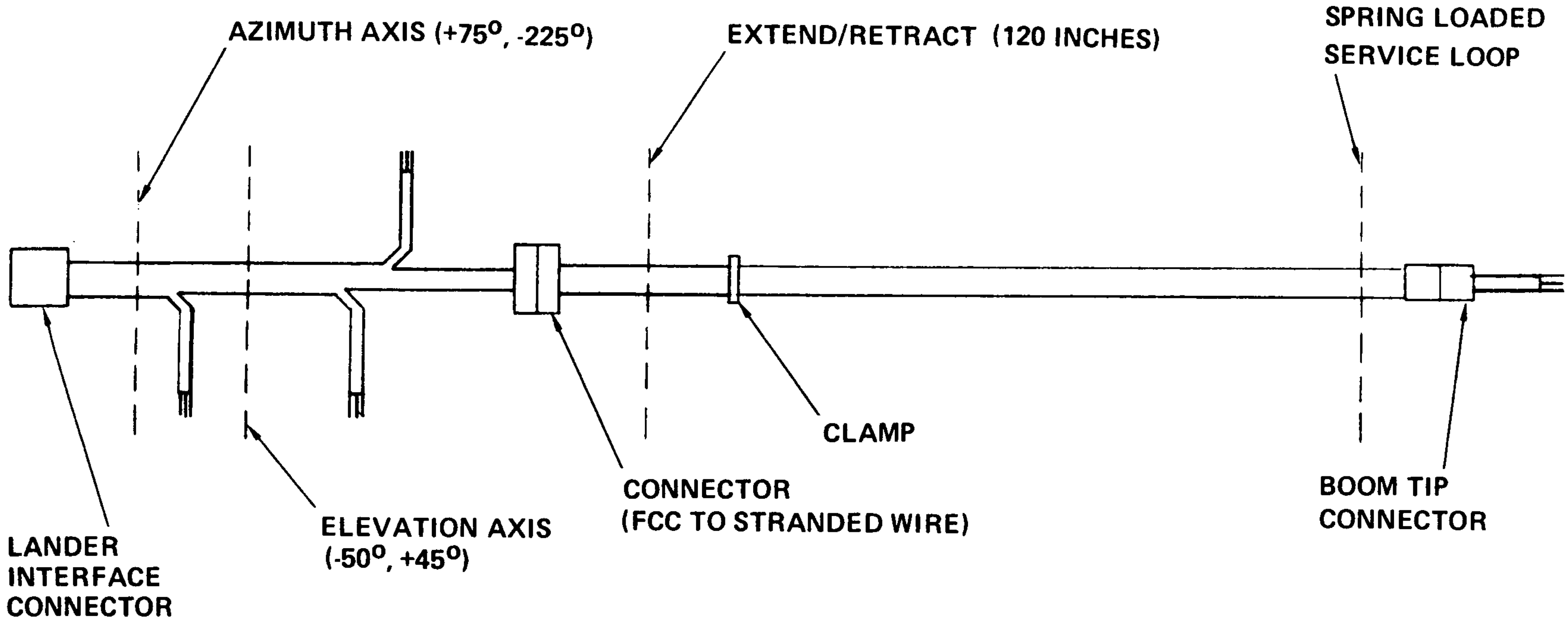


Figure 2. Interconnect Assembly Diagram

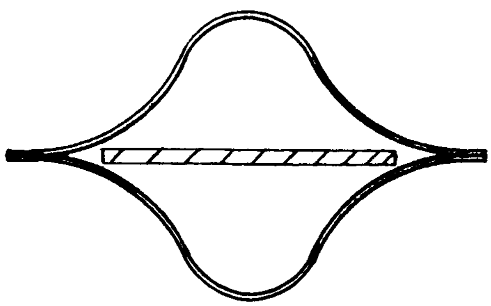


Figure 3. Boom Cross-Section — Extended

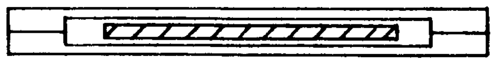


Figure 4. Boom Cross-Section - Retracted

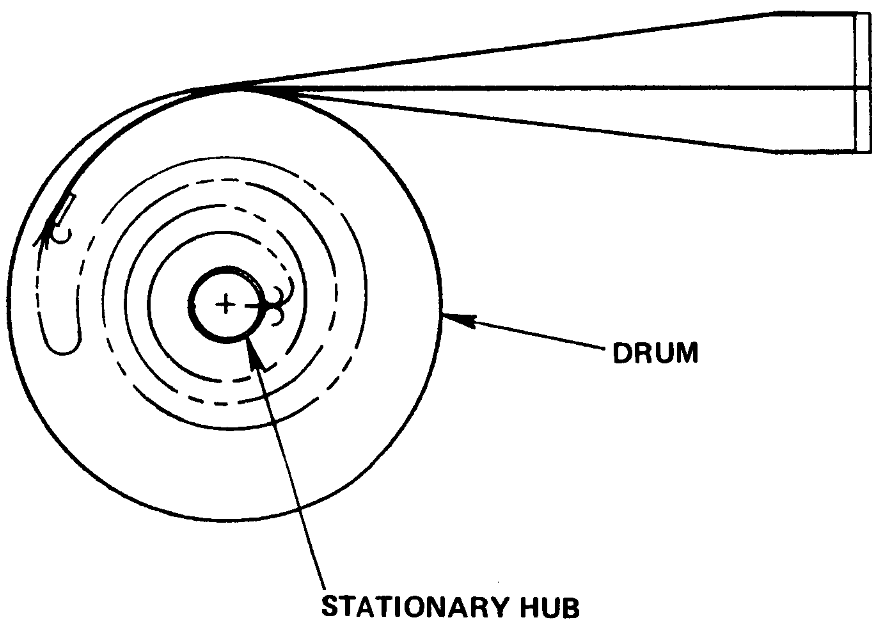


Figure 5. Drum and Hub Assembly

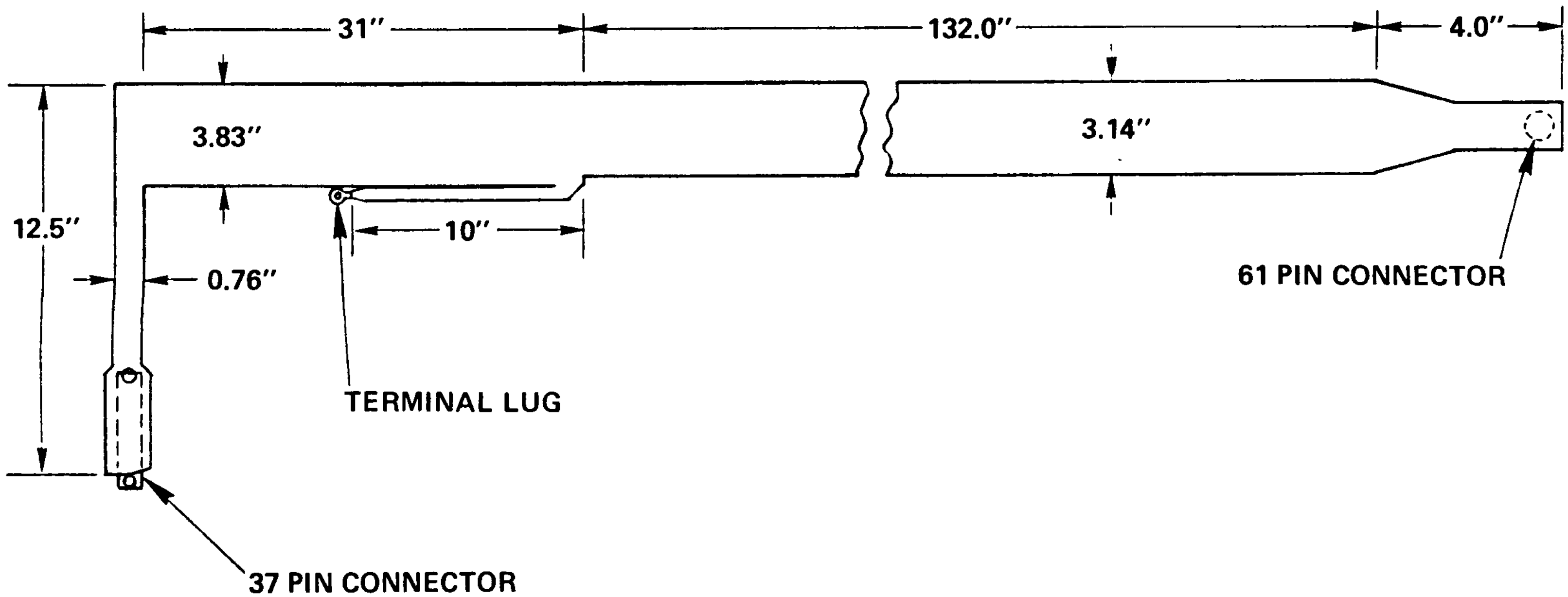


Figure 6. FCC Assembly Plain View

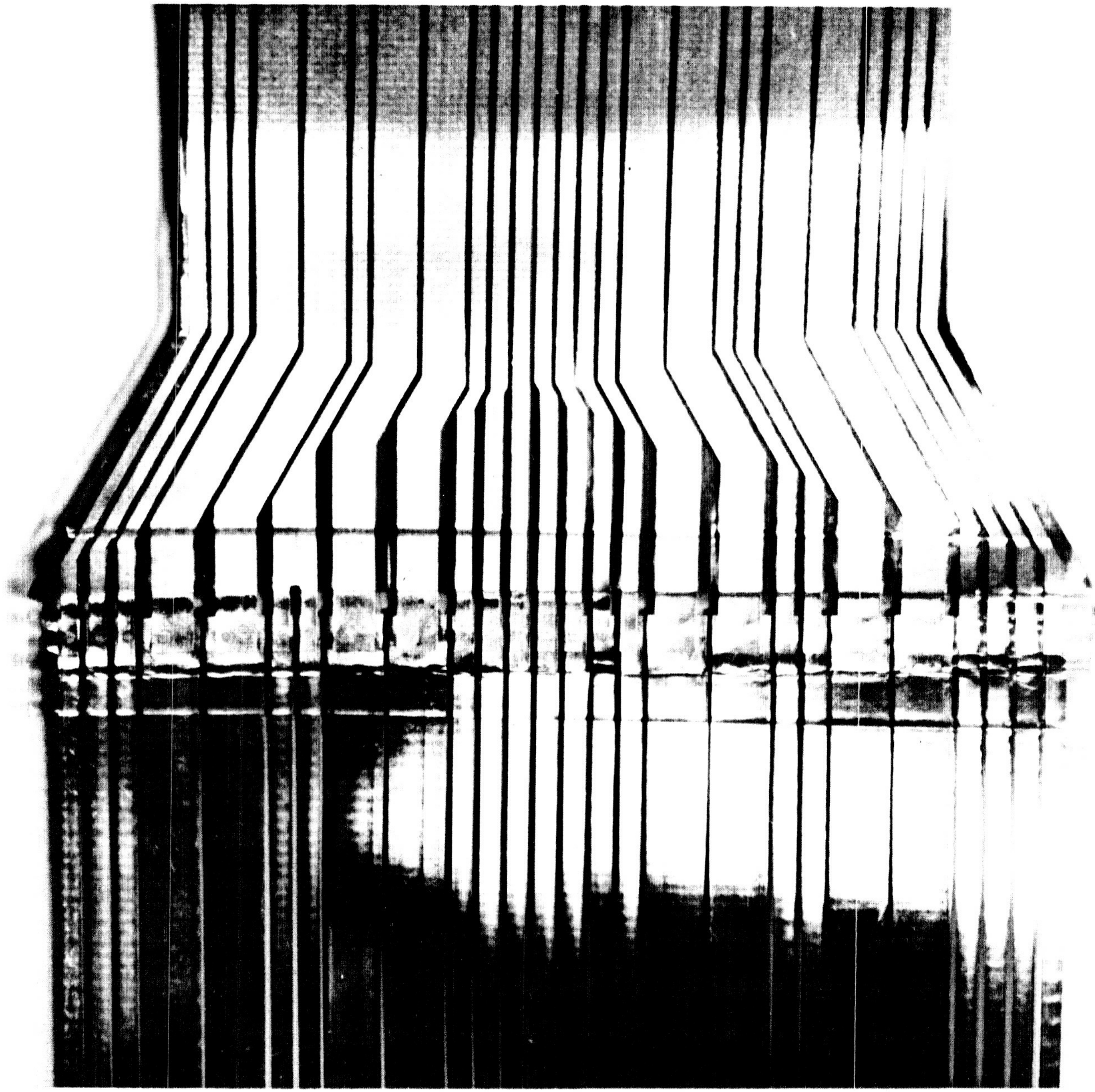


Figure 7. Welded Connections at Boom Tip

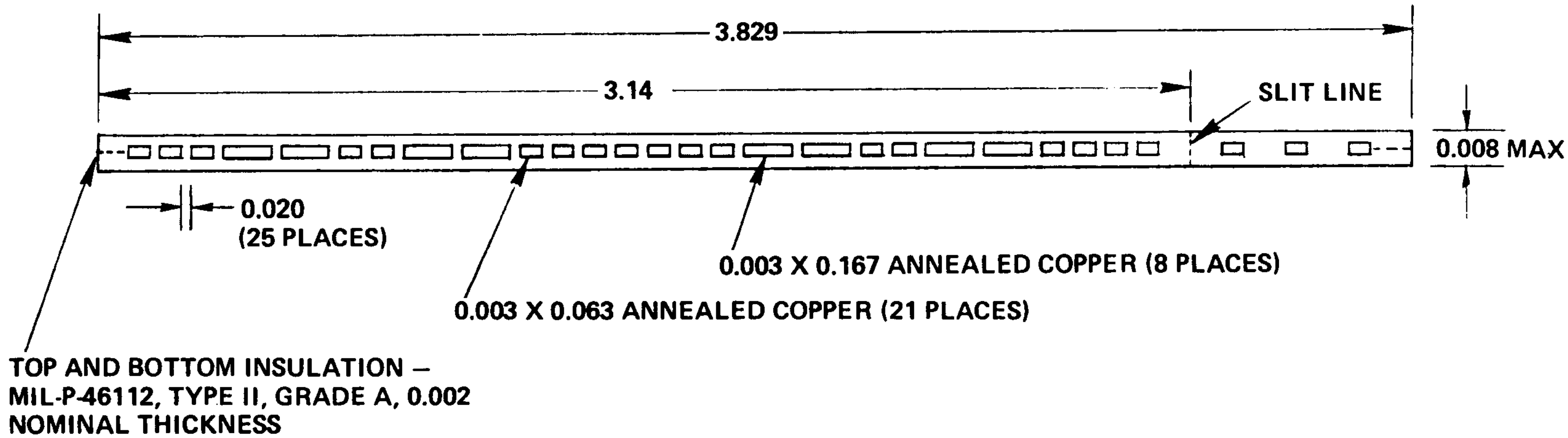


Figure 8. Collated Cable Configuration

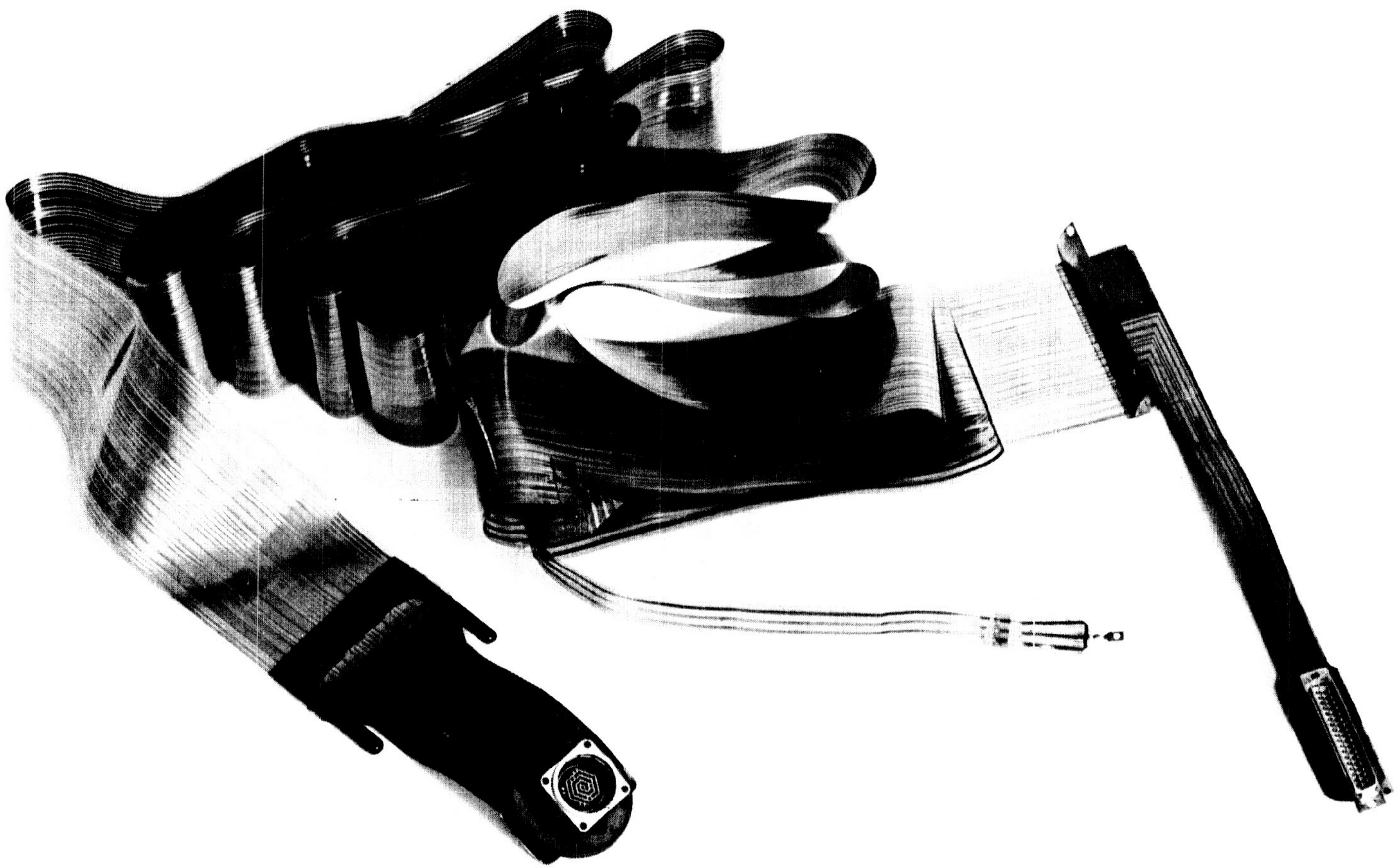


Figure 9. Viking Boom Flat Conductor Cable Assembly

MILITARY AND AEROSPACE APPLICATIONS OF FCC

By Candace Swanson
Hayes International Corp.

Introduction

Flat conductor cable (FCC) technology has now reached a level of development where it is being considered for, and used in numerous interconnection projects. The following selection of Government-sponsored programs demonstrates the large number and remarkable variety of ways in which FCC has been successfully used by the Government. Although the majority are NASA-funded, a few military-directed projects are also discussed. A report recently completed by Mr. W. Angele at NASA/MSFC contains information on these and additional FCC applications, both commercial and Government-sponsored. [1]

FCC Applications

Saturn IVB Study

To gain experience and to arrive at sound figures relative to the pros and cons of flat cable systems, NASA/MSFC let a contract to McDonnell Douglas which called for an engineering and installation study of the aft skirt areas of the Saturn IVB stage. As part of this study, completed in 1966, a mockup was made using a total of 50,000 conductor feet of FCC. A section of this 180-degree aft skirt mockup is shown in Figure 1.

The Kapton/Teflon-insulated flat cable used in the mockup was supplied by Methode Electronics. It ranged in widths from 1/2 inch to 3 inches, and contained from six to 38 conductors on 75-mil centers. Some of the cable was shielded. Cable was terminated primarily to NASA rectangular FCC connectors.

This flat cable installation study proved the feasibility of the flat cable system and showed great savings in weight, time, and

material cost. In replacing round wire cable with FCC, the following savings were realized: weight (mounting hardware and harnesses), 76 percent; time (cable assembly and installation), 70 percent; and cost of materials (cable, plugs, fasteners), 33 percent. Using current cable prices, material savings for the same mockup would be closer to 72 percent.

Pegasus Meteoroid-Detection Satellite

The highly successful Pegasus meteoroid-detection satellites (Fig. 2), built by Fairchild-Hiller Corporation for NASA/MSFC in 1965, used FCC in two areas. Flat cable was the interconnection medium for the deployable detector-panel wings, conveying meteoroid penetration data from the aluminum panels to the instrumentation canister of the spacecraft. Also, FCC was the link between canister and attitude control sensors as well as temperature sensors located in the forward solar array.

All of the Methode-produced FCC was Mylar insulated. Wing cable was predominantly unshielded, while cable to the solar array was shielded. On each wing, 24 eight-conductor flat cables were used, some measuring 65 feet in length. Four harnesses of six FCC layers each carried conductors from the wing tip to the center section structure and then to the instrumentation canister. On the wing, cables were "threaded" along the front of one wing section to the back of the next. Conductors were branched at selected locations and soldered to flexible circuit bus bars from which ground and signal round wires led to detector panels. In the solar array, cables were solder-terminated to AMP connectors at the instrumentation canister's junction box.

Cable flexibility, particularly critical at the hinge sites of the deployable detector-panel wings, was a major requirement leading to FCC selection. Use of FCC also resulted in a significant weight savings.

Solar Array For Skylab Orbital Workshop

In 1969, FCC was used by NASA/MSFC in the initial design of the solar array for the orbital workshop of the Skylab operation. Flat cable, selected for its low profile and small bend radius characteristics, provided power and instrumentation interconnections between

the solar array surfaces and wing junction boxes. Figure 3 is a model of a wing portion, with typical cable routing during deployment.

Two types of cable were used, both produced by Micro Cable (now part of Parlex Corp.). The 1/2-inch wide instrumentation cable contained six 4 X 40 mil conductors, while the 2-inch power cable contained 5 X 125 mil conductors. Both cables were Kapton/Teflon-insulated. FCC was pressure-terminated to edge connectors on the array wing surfaces, and terminated to standard NASA FCC 75-mil contact center plugs at the junction boxes. These plugs (and mating receptacles) were modified to accommodate power cables. The power cable is designed to convey power from approximately 1200 square feet of solar array surface, with a total capability of 12 kilowatts of power. Thirty temperature measurements were to be taken from the array by the signal cable.

Poseidon Missile (GSE)

Lockheed Missiles and Space Company uses flat cable jumpers in ground support equipment (GSE) for the Navy's Poseidon underwater-to-ground missile. These cable assemblies, manufactured by Ansley Electronics Corporation, are used for hinging panels in automatic digital test and checkout equipment for guidance and control electronics.

A total of 95 flat cables terminated with miniature connectors form jumpers from door to cabinet and from door to door (Fig. 4), thus maintaining electrical continuity while doors are opened and closed. Jumper cables contain seven conductors, two of which are large conductors to accommodate power circuits. All contacts are welded to flat conductors through the insulation. Long flex-life, minimum space requirements, and reliable terminations combine in a trouble-free design.

Upstage Missile

In the guidance command unit of the Army Upstage Missile, McDonnell Douglas uses flat jumper cables to interconnect PC cards, multilayer boards, and thick film substrates. Two basic types are used. The 6-inch wide Mylar-insulated jumper cables procured from Methode contain fifty-nine 5 X 50 mil conductors on 100-mil center spacing. Figure 5 shows the 6-inch cable in the guidance command unit. The second type cables are Ansley West Flexstrip. These are from 2 1/2 inches to 3 1/2 inches wide and contain from twelve to seventeen 5 X 25 mil conductors on 200-mil center spacing. Teflon

insulation is utilized.

Electronics Control Equipment For Neutral Buoyancy System

FCC is being used for a drawer type application in the electronics control room for NASA/MSFC's neutral buoyancy system, a complex used for simulating the zero-g environment of space. The FCC connects electronics in sliding panel assemblies of four instrumentation units, two Systems Engineering Consoles and two Bio-Medical Display Meter Racks, with the main distribution rack. The panel assemblies remain electrically operational while drawers housing them are opened or closed. As a result, troubleshooting and checkout efforts are vastly simplified.

A total of 18 meter panel assemblies are used in the Systems Engineering Consoles and the Bio-Medical Display Meter Racks. These panel assemblies are on standard Jonathan slides, with FCC as the interconnecting cable to allow for accessibility and quick repair of assembly components. When necessary to remove the complete panel assembly, it can be easily disconnected from the rack and unplugged from the FCC. Figures 6 and 7 depict an assembly in the open and closed positions. In each panel assembly, 72 flat conductors are available for use with electronic components. This is accomplished by using four Methode-produced 1.5-inch Kapton/Teflon-insulated flat conductor cables, each with eighteen 4 X 40 mil conductors on a 75-mil center spacing. Each pair of flat conductor cables is routed along the insides of the assembly slides and terminated to a 36-conductor standard NASA rectangular plug which mates to an FCC to round wire receptacle. Round wire from the receptacle is then routed to instrumentation in the drawer. From the panel assemblies in the Systems Engineering Consoles and Bio-Medical Display Meter Racks, the 30-foot lengths of FCC are routed to the main distribution rack, where cables are terminated to the same type connector assembly previously described.

MK 48 Torpedo Fire Control System (FCS)

The MK 48 Torpedo Fire Control System manufactured by Librascope Division of the Singer Company (Fig. 8) contains highly flexible FCC harnesses to connect major unit subassemblies. The harnessess are fabricated by Ansley Electronics Corporation.

Limited space and extreme flexure requirements dictated use of FCC. Some equipment sections had to move both in and out and pivot 90 degrees to allow service accessibility. Equipment had to be operational at all times. A corrugated FCC was selected to meet these requirements, providing almost unlimited flex life and a 20 percent savings in space.

Most of the Teflon-insulated flat cable contains 20 conductors, although some cable with higher current requirements has a smaller number of wider conductors. Additional cable features include shielding on both sides and conductor termination by welding.

Naval Shipboard Equipment

Librascope Division of the Singer Company used FCC for power distribution as well as digital and analog transmission in a naval shipboard electronics equipment design (Figs. 9 and 10). FCC was selected as the interconnecting medium primarily because

1. Use of FCC enabled drawers to be extended to a service position while equipment continued to operate,

2. Conventional round wire assemblies could not be fitted into allocated space, and

3. Cost reductions were possible through use of simplified and standardized (a) cable termination techniques and (b) designs for shields and harness assemblies.

Most of the 2-inch wide, Mylar-insulated cables contained 19 conductors, equivalent to size 24 AWG. Power cables contained 4 conductors, each approximately 16 AWG in area. A separate shield laminate was selected for the interconnect design. The AMP-UNYT (Trademark of AMP Inc.) insulation piercing system was used to terminate conductors and shields.

F-111 Airplane: Mark II Avionics

Autonetics Division of North American Rockwell Corporation applied flat cable packaging techniques to inertial navigation equipment in the Mark II Avionics of the F-111, an Air Force plane. Conversion to FCC actually saved 800 labor hours per assembly in production and reduced assembly weight by 3 1/2 pounds. Also, reliability was remarkably improved and wire breakage due to handling was completely eliminated due to the cable convolutions which acted as flexible service loops.

Within the equipment, flat conductor jumper cable assemblies (Ansley Electronics Corporation) are used to connect boards to input/output connectors. Corrugations in the flat cable serve as service loops for ease in installation, and provide float for vibration isolation. Figure 11 depicts a completed instrument package.

Lunar Surveyor

Flat cable constructed to meet specific electrical requirements interconnected spacecraft electronics and the sensor of a 29-pound alpha-scattering unit used to analyze the lunar surface. The unit is shown in Figure 12. Of the five successfully landed Lunar Surveyors, designed and built by Hughes Aircraft company under the direction of NASA/JPL, three contained the alpha-scattering unit.

The FCC contained 4 X 40 mil conductors for temperature sensors and heaters, special configuration 3 X 10 mil conductors for alpha and proton gates, and 3 X 25 mil conductors for proton sensors. Sprayed-on silver paint was used for the shield, and contact was made directly to grounded conductors through prepunched holes in the insulation.

Lunar Portable Magnetometer (LPM)

To obtain measurements of the permanent lunar magnetic field at various sites, NASA/Ames Research Center designed, developed, and fabricated the Lunar Portable Magnetometer (LPM). This system, shown in Figure 13, is a modification of the one used by Bendix in the ALSEP System. Fifty feet of FCC manufactured by Parlex Corp. connects the sensor head (mounted on a tripod) with the electronics and data display assembly (located on the transporter). The FCC is housed in a reel assembly which provides a rewind as well as a deployment capability. This reel assembly (Figure 14) was developed by NASA/MSFC to meet critical weight and volume packaging limitations. As a result, the complete assembly weighs only about 2.5 pounds, and measures less than the design maximum of 3.6 inches in diameter and 4.0 inches in height. Because of its flat configuration, flexibility, and high packaging density, FCC provides a low weight and smooth deployment cable system for the experiment.

The flat cable used is 2.5-inch, 32-conductor (3 X 50 mil), Kapton/Teflon-insulated. The cable is terminated to the elec-

tronic package by a NASA standard 2.5-inch plug and receptacle, and to the sensor head by an FCC to round wire transition which becomes an integral part of the sensor head assembly.

Advanced Action Manipulator System (ADAMS)

The ADAMS (Fig. 15) is one of a group of low cost, electromechanical manipulators which are under development for the performance of tasks such as handling, loading, transferring, stacking, and assembling in space and in other harsh environments. The basic assembly will be coordinated with various MSFC and other NASA organization systems to comprise ultimate systems. FCC was selected to replace original round wire cables because of greater flexibility, reliability, and packaging density factors.

Two FCC flexible spring coil assemblies, provided by NASA/MSFC, are used in the manipulator. The center coil of one is located in the shoulder joint (Figure 16), allowing $\pm$ 170 degrees rotation and an elevation of +200 degrees from the vertical down position of the upper arm. The second coil is centered in the elbow joint, and again allows rotation of $\pm$ 170 degrees. Elbow pitch of -60 degrees to +140 degrees is also possible. Each cable assembly consists of two layered cables, terminated at one end to a standard NASA circular 1/2 inch plug, and at the other end to an FCC to round wire transition. Plugs of both assemblies connect a feed-through receptacle below the shoulder joint, thus enabling quick disconnect of the ADAMS from the base structure. The flat cable used is Kapton/Teflon insulated, 1/2 inch wide, and contains six 4 X 40 mil conductors on a 75-mil baseline center to center spacing.

Apollo Telescope Mount (ATM)

FCC will be used for conveying electrical signals across the torque-sensitive gimbal assembly of the ATM Unit 705 (caging and gimbal assembly). The ATM, part of the Skylab operation, is being designed and built by NASA/MSFC. The schedule for fabrication and use is fixed and accepted.

Flat cable was selected over round cable for three major reasons.

1. The extreme flexibility of FCC permits rotational motion of $\pm$ 120 degrees in the roll adapter. Routing and securing of FCC in this area is shown in Figure 17.

2. Using FCC, torque reductions of up to 90 percent could be achieved, a critical requirement for proper functioning of the gimbal system. A model depicting the general principle of crossing the gimbal system with minimum torque is shown in Figure 18. The actual way in which FCC crosses the gimbal system is shown in Figure 19.

3. Because of its high packaging density characteristics; FCC could be fitted into the cable arch which houses the cable from the roll adapter to the roll ring of the gimbal system. A redesign of the cable arch to permit use of the bulkier round wire cable would have necessitated major revision of the 705 Unit.

Two types of FCC, fabricated by Parlex Corp., will be used. The 2.5-inch signal cable is Kapton/Teflon insulated and contains thirty-two 3 X 50 mil conductors on 75-mil centers. The 2.5-inch power cable is also Kapton/Teflon insulated and contains eight 3 X 250 mil conductors on 300-mil centers. Half-mil strips of copper shielding , 2.5 inches wide and Kapton/Teflon insulated, will be alternated with the FCC. To assure greatest possible cable flexure, the copper shielding will not be bonded to the FCC. Approximately 180 layers of cable and shielding will carry a total of 2500 conductors across the two gimbal interfaces to the experiment-containing canister. A total of 124 FCC to round wire transitions will be used in the ATM.

Conclusion

These examples represent only a few of the numerous ways in which flat conductor cable has been used by the military and by NASA. However, they do serve to point up the number and great diversity of flat cable uses.

FCC has found wide application in everything from the integration of lunar equipment to the packaging of electronics in nuclear submarines. It has been used to cross hinge-lines in satellites, interconnect electronics in equipment drawers, cross gimbal rings in the Apollo Telescope Mount. It has been permanently corrugated or coiled in reels for deployment capabilities, and twisted or imaginatively looped to enable parts to rotate. It has met stringent project requirements of low volume, low weight, flexibility, low costs, low torque, and high reliability.

FCC application technology has certainly come a long way since the early 60' when cable uses were largely limited to study-type

projects, to the replacement of round wire, and to very simple cable routing techniques. Unfortunately, even today the full potential of flat conductor cable systems is not being made use of. However.........

(1) As the production of cable and associated hardware increases, bringing with it lower costs;

(2) As flat conductor cable technology expands (particularly in the area of connecting hardware) and items become readily available;

(3) As designers become more familiar with the potential of flat cable systems, and begin thinking in terms of FCC in the first stages of a project - rather than after limits have been set; and

(4) As experience in flat cable application technology increases and becomes widely known -

We will then see (as has been evidenced most recently) a great increase in the general usage of FCC systems. Once such considerations as cost, adequate connecting hardware, and hesitance to use new technology have been dealt with, flat conductor cable will no longer be used primarily in unique Government projects. On the sole basis of its merits, flat conductor cable will be a commonly used, acceptable choice for numerous interconnection tasks.

Reference 1. Angele W.: Flat Conductor Cable Applications, NASA TM X-64672, 1972

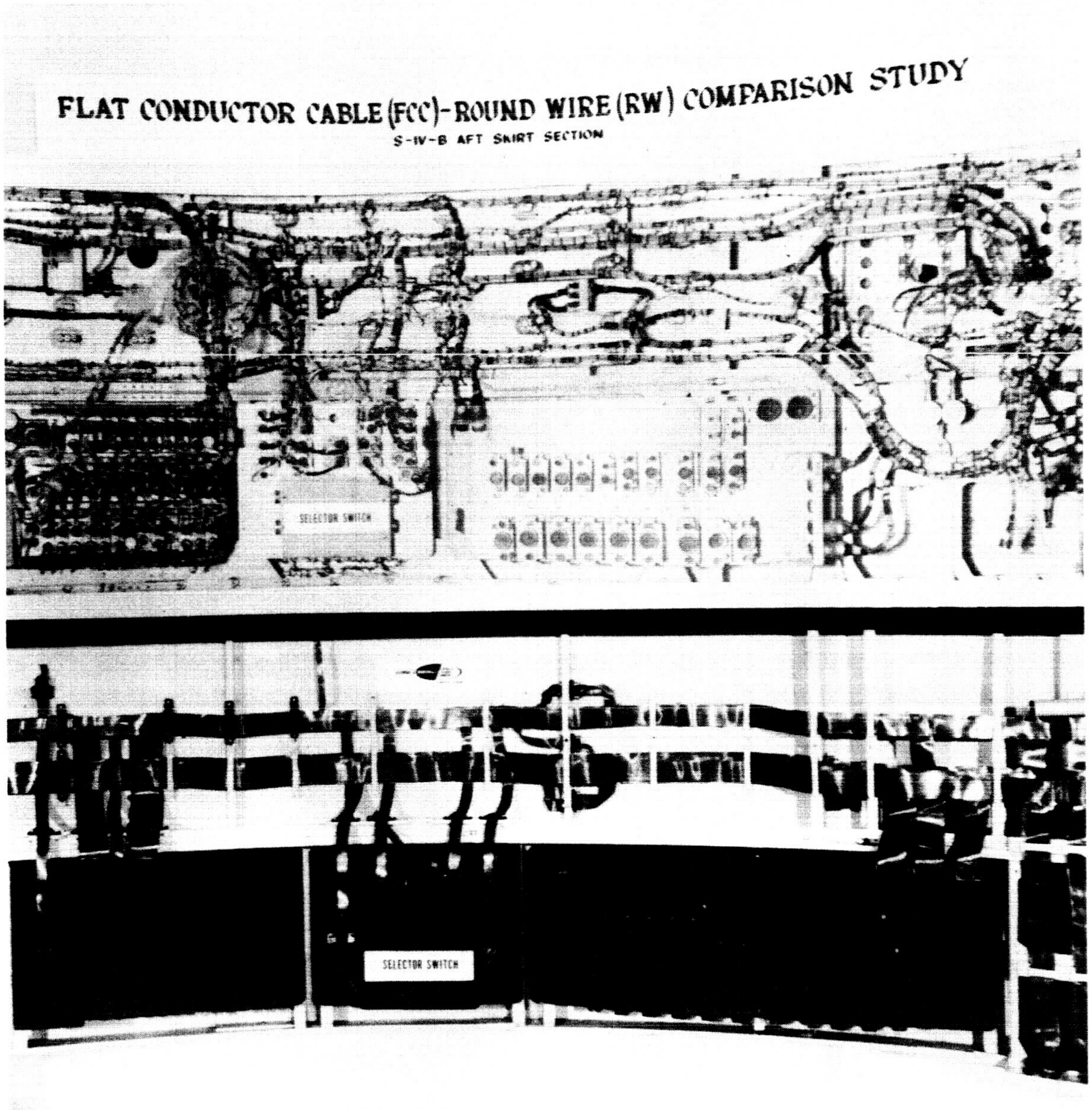


Figure 1. FCC versus RWC comparison, Saturn IVB aft skirt mockup.

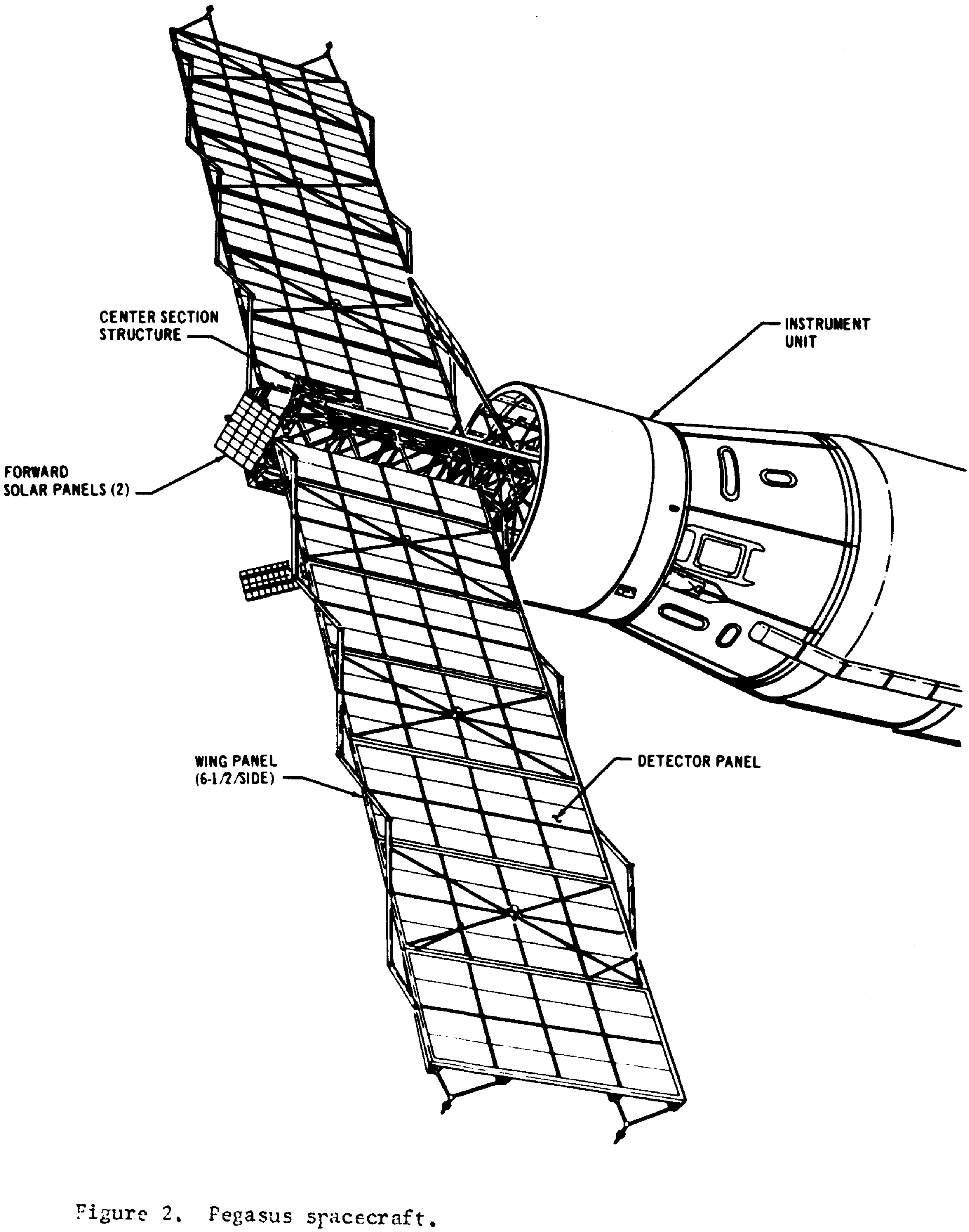


Figure 2. Pegasus spacecraft.

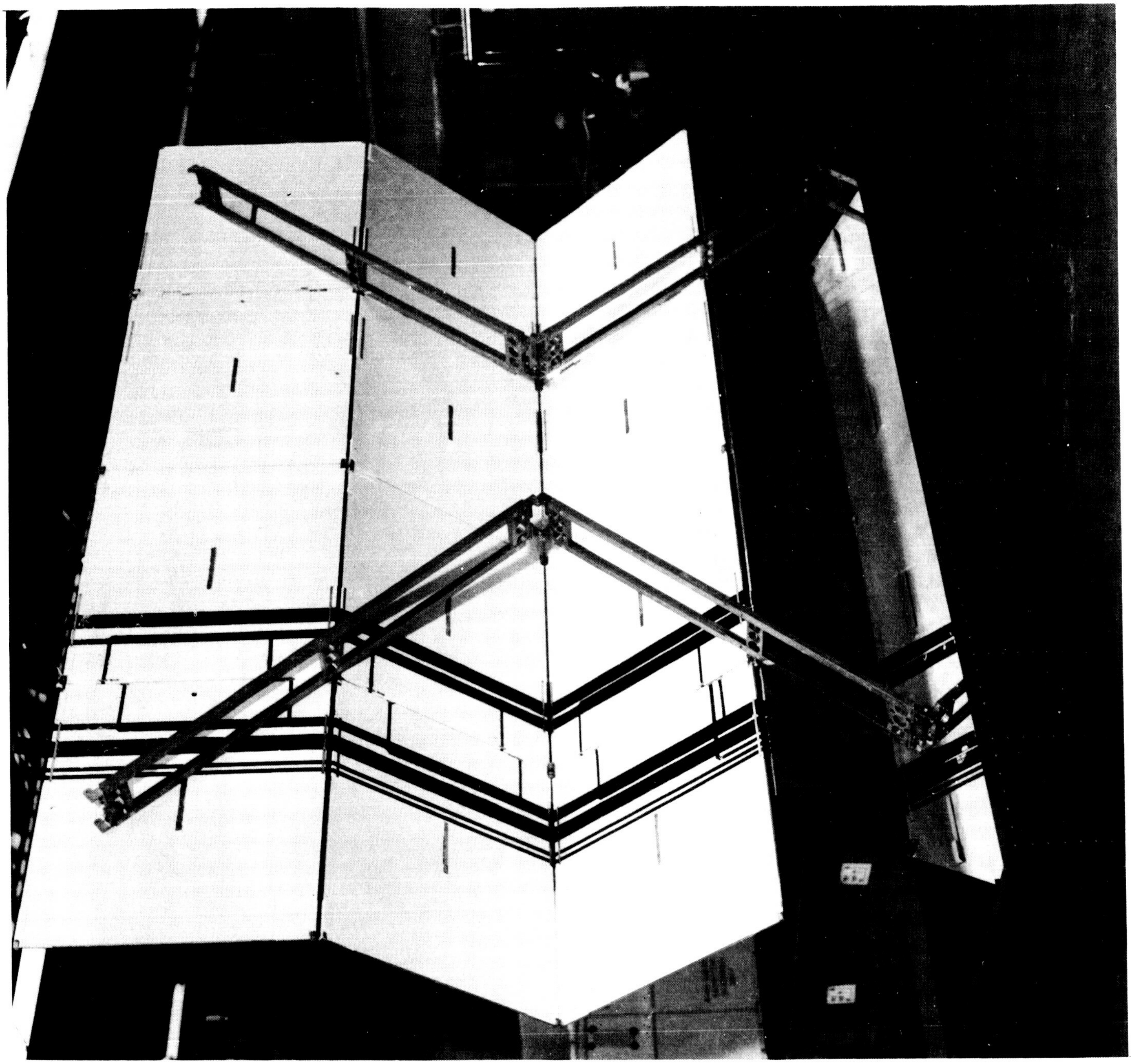


Figure 3. Model of wing portion depicting typical cable routing during deployment.

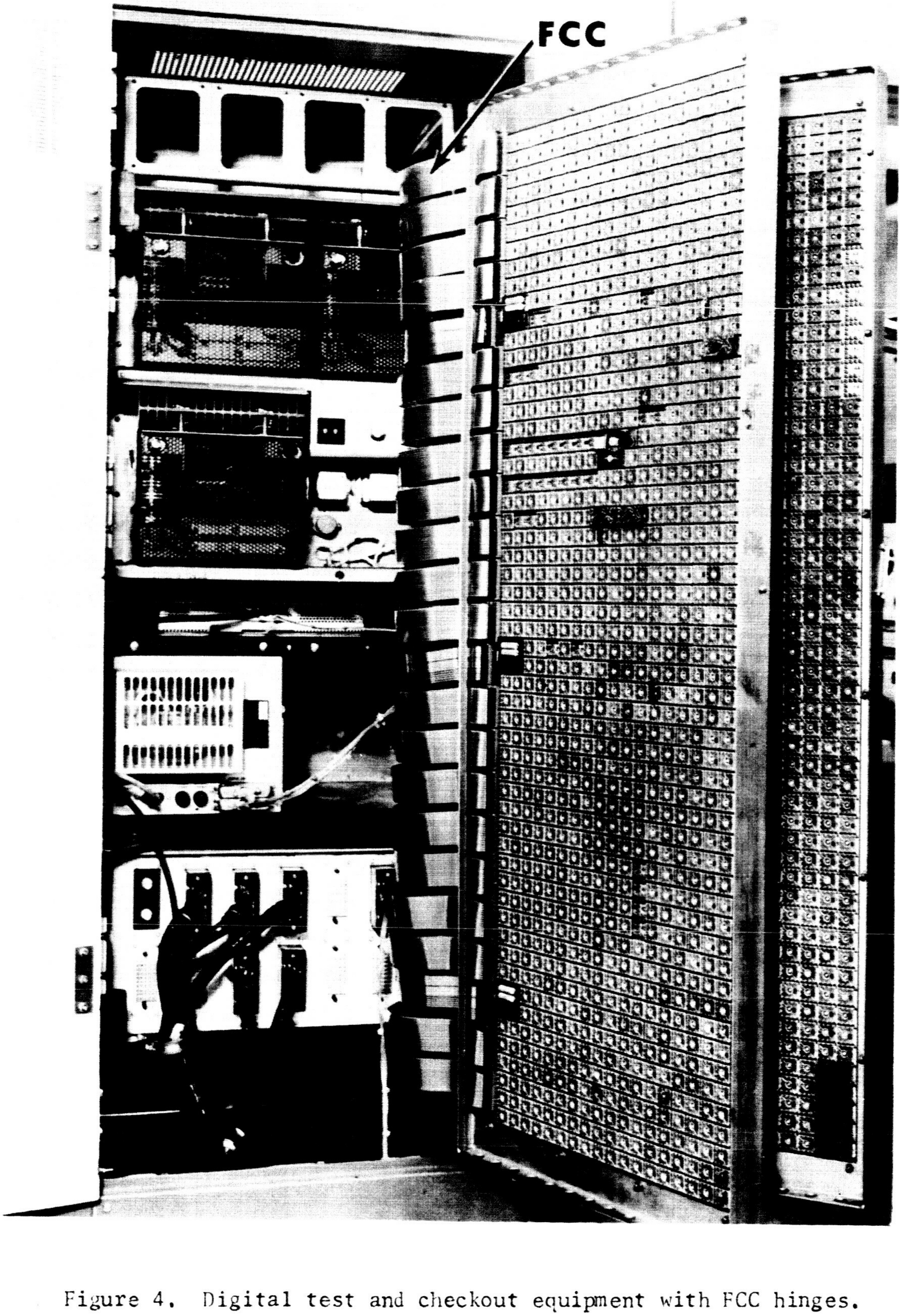


Figure 4. Digital test and checkout equipment with FCC hinges.

Figure 5. 6-inch flat jumper cable in Upstage Guidance Command Unit.

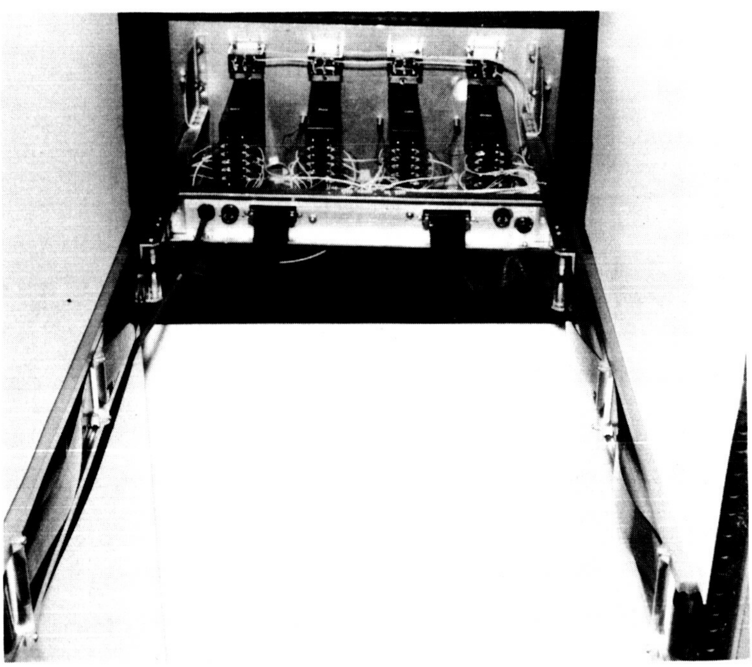


Figure 6. Panel assembly in open position.

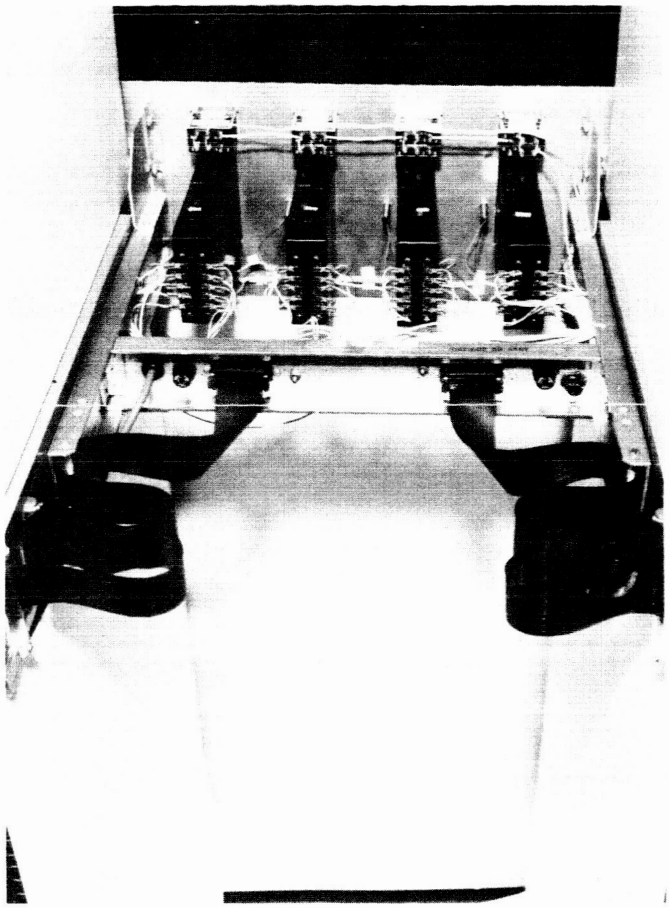


Figure 7. Panel assembly in closed position.

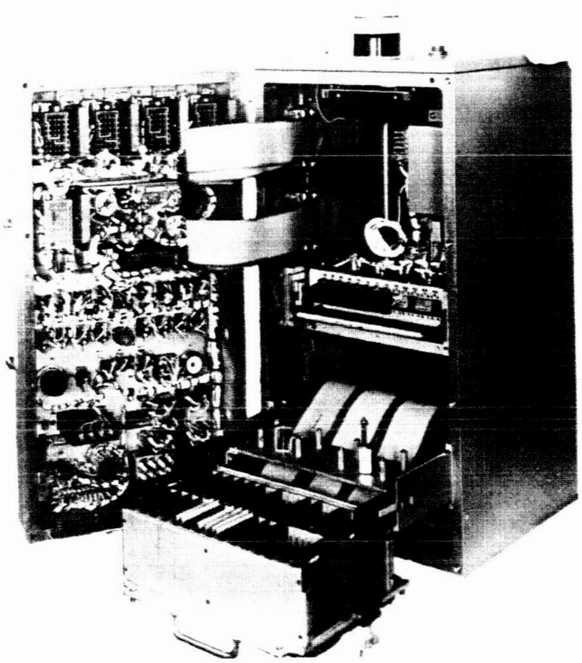


Figure 8. MK 48 Torpedo Fire Control System.

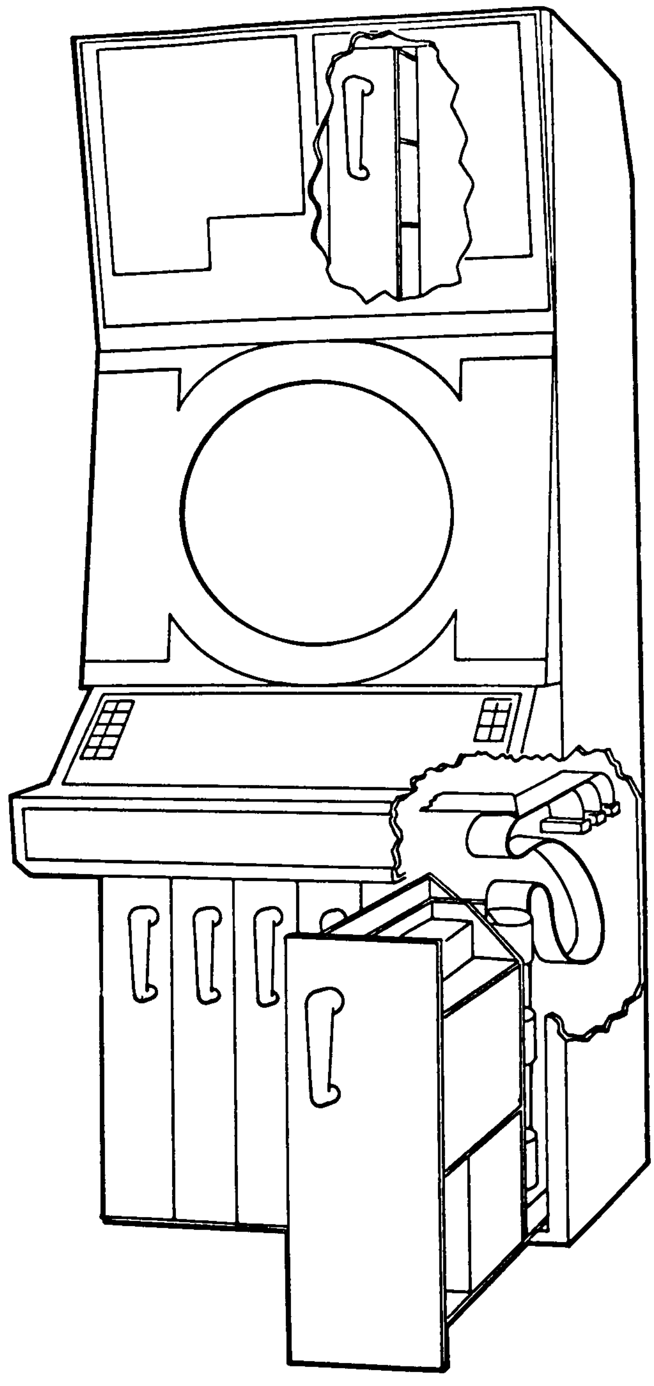


Figure 9. Conceptual packaging drawing.

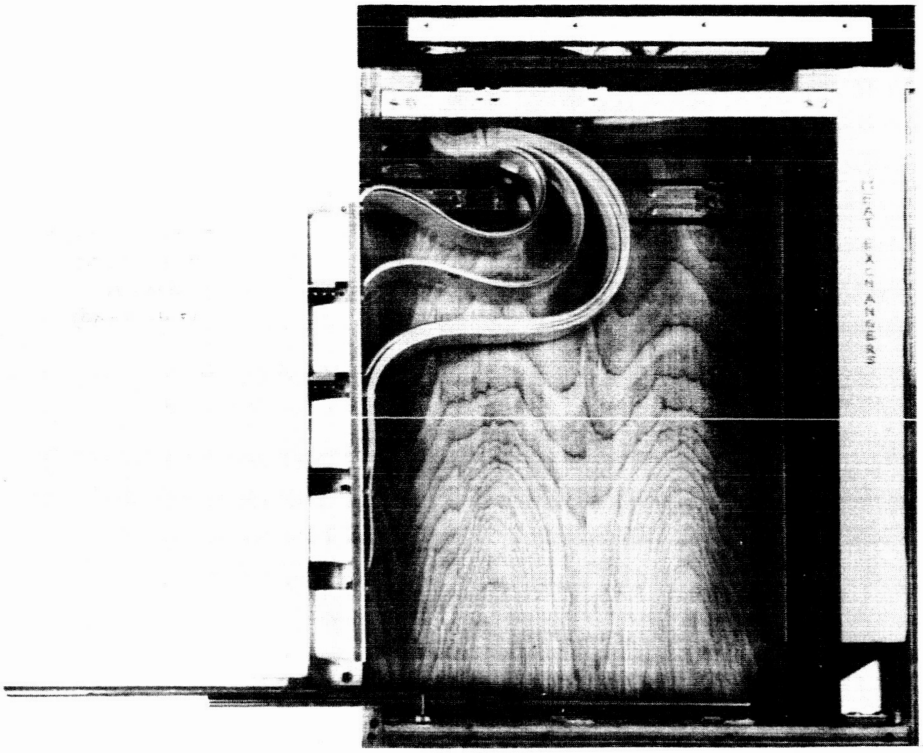


Figure 10. Mockup of a typical drawer in service position.

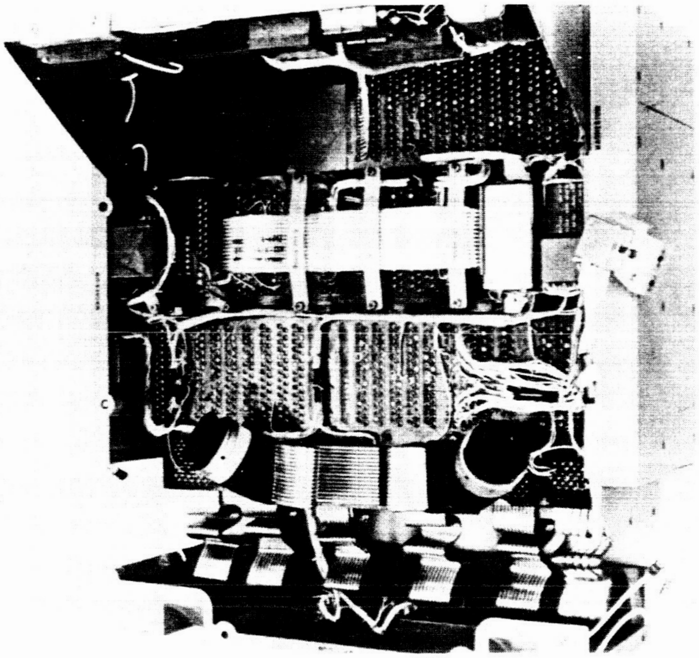


Figure 11. Inertial navigation assembly with FCC.

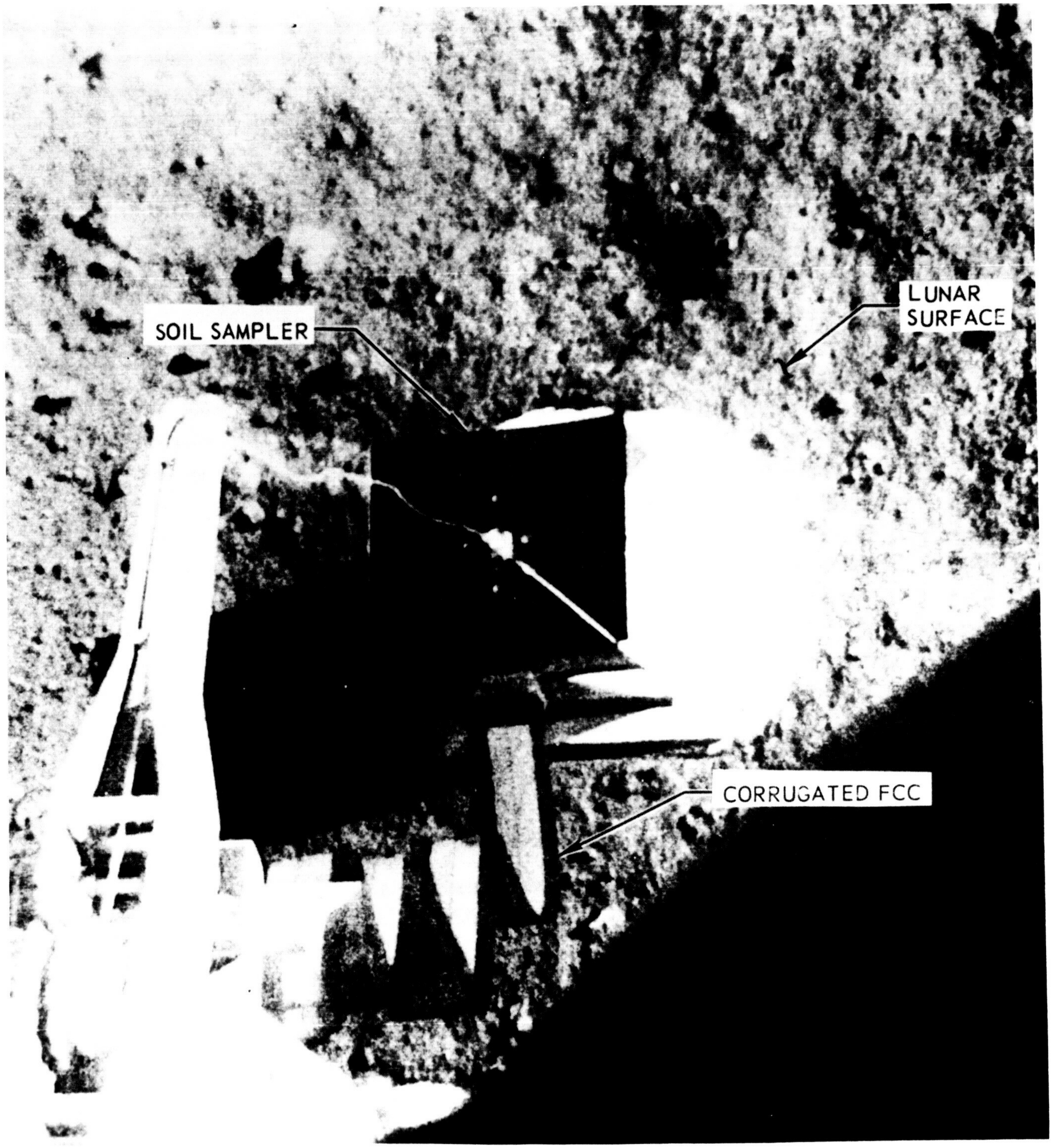


Figure 12. FCC harness on Hughes Lunar Surveyor V Spacecraft, flown in 1967.

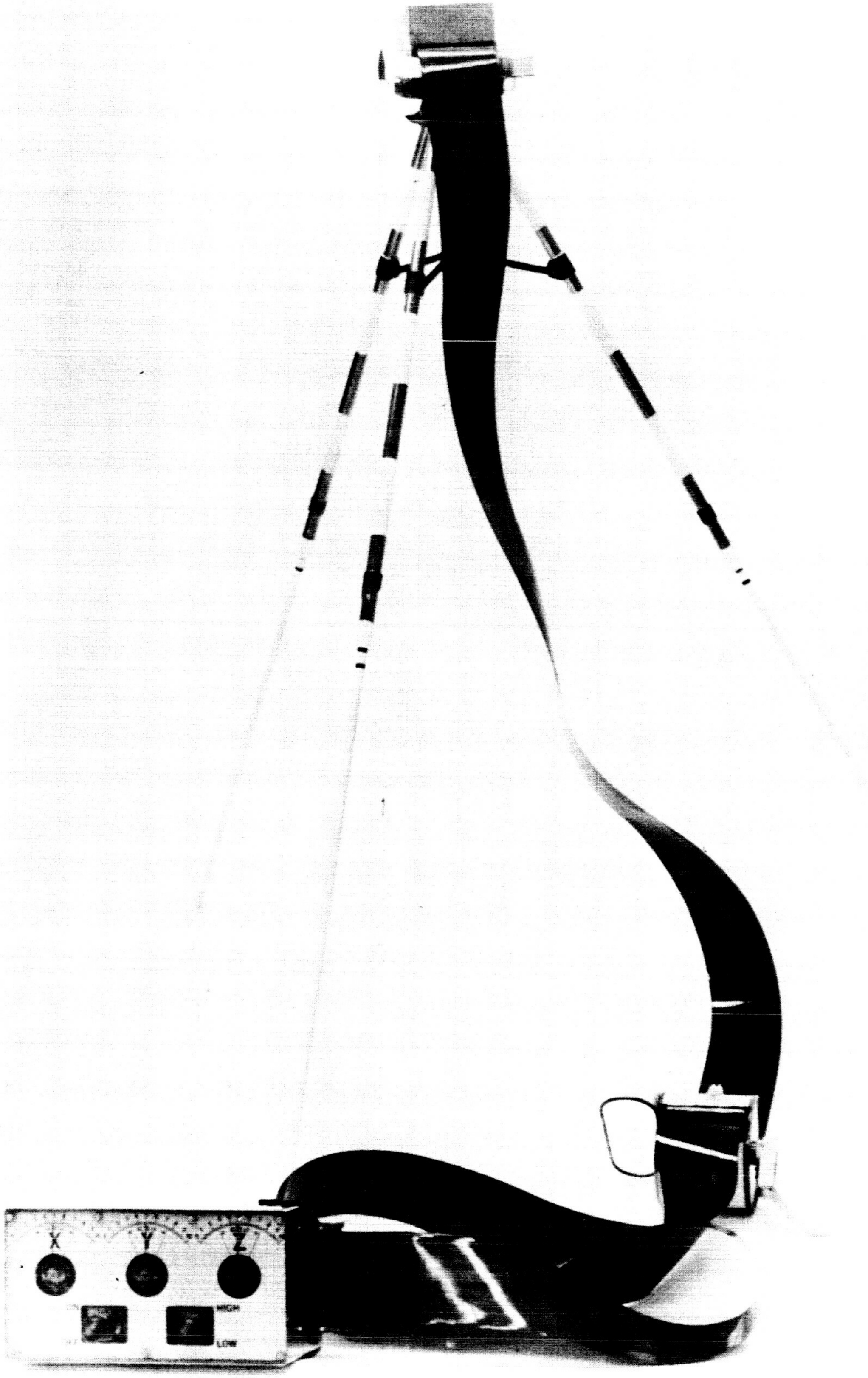


Figure 13. Tripod - sensor, reel, and electronics box assemblies.

Figure 14. Reel assembly developed by NASA/MSFC.

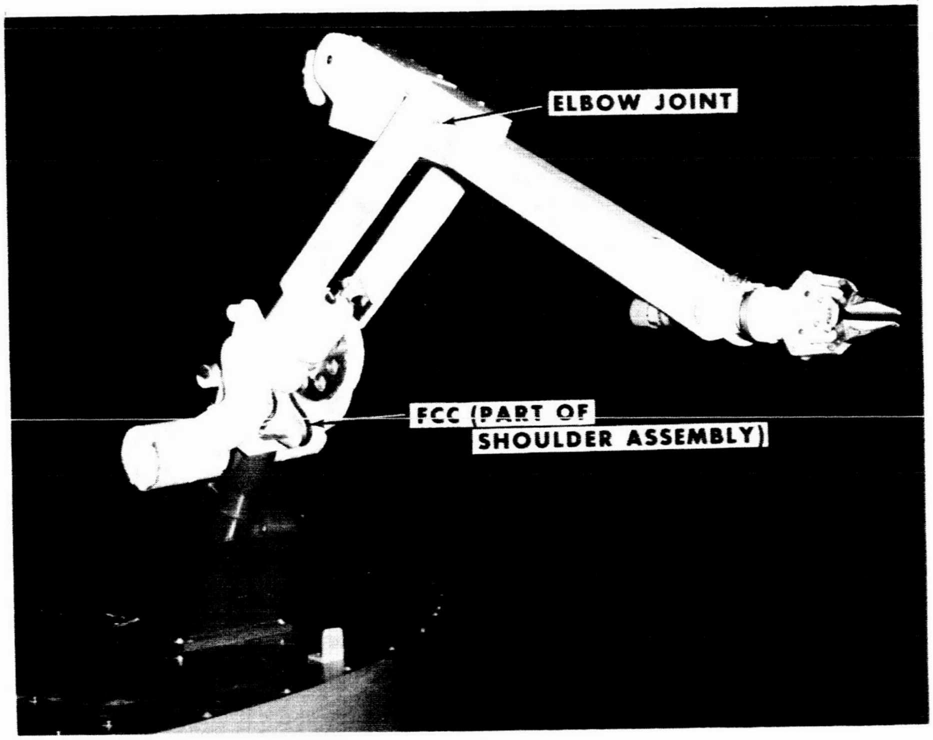


Figure 15. Overall view of ADAMS.

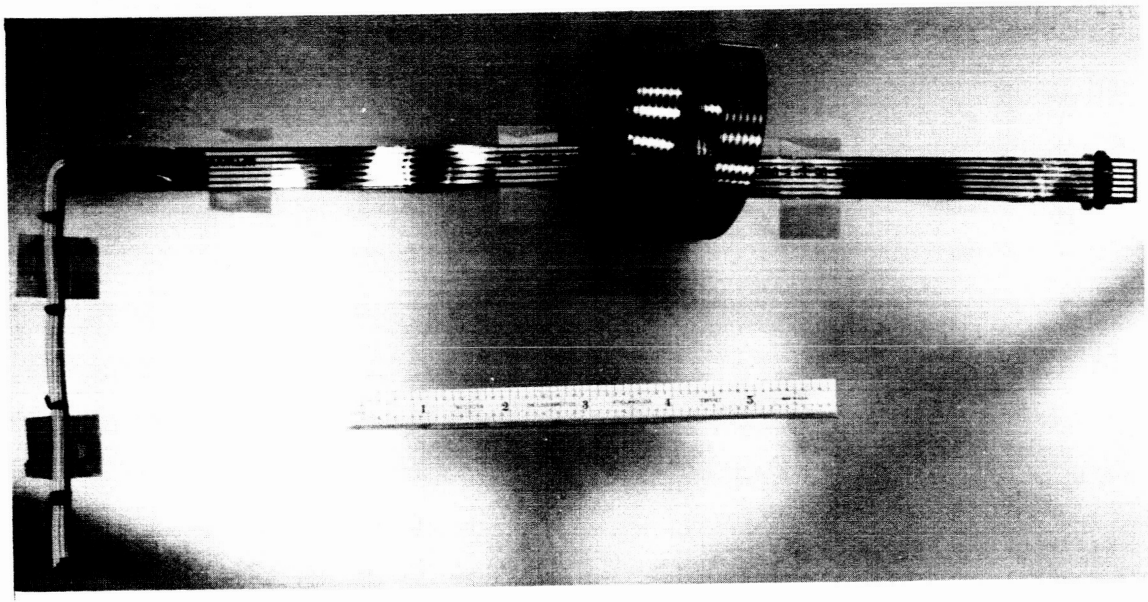


Figure 16. ADAMS shoulder coil.

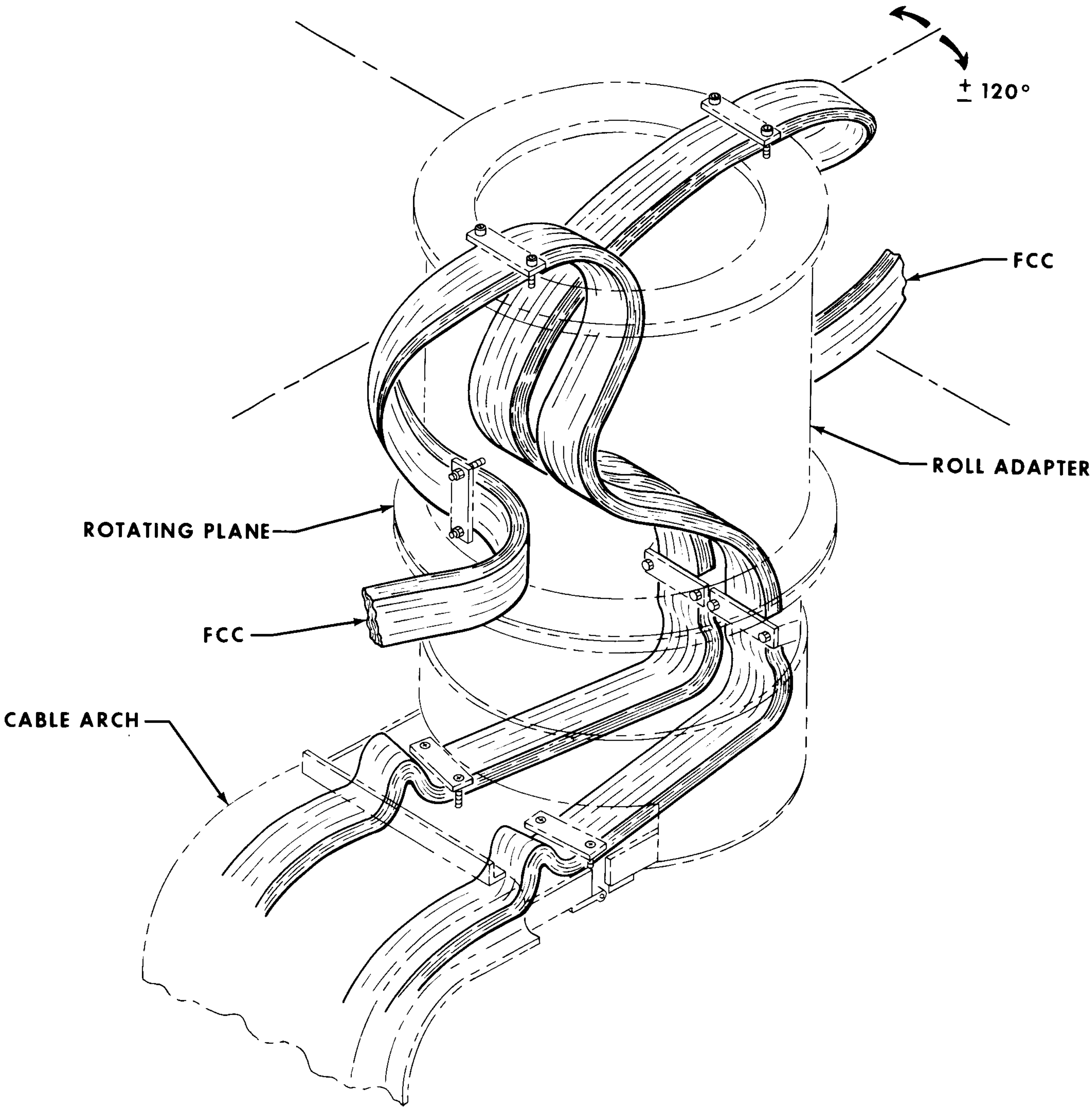


Figure 17. FCC routing and securing in the ATM roll adapter.

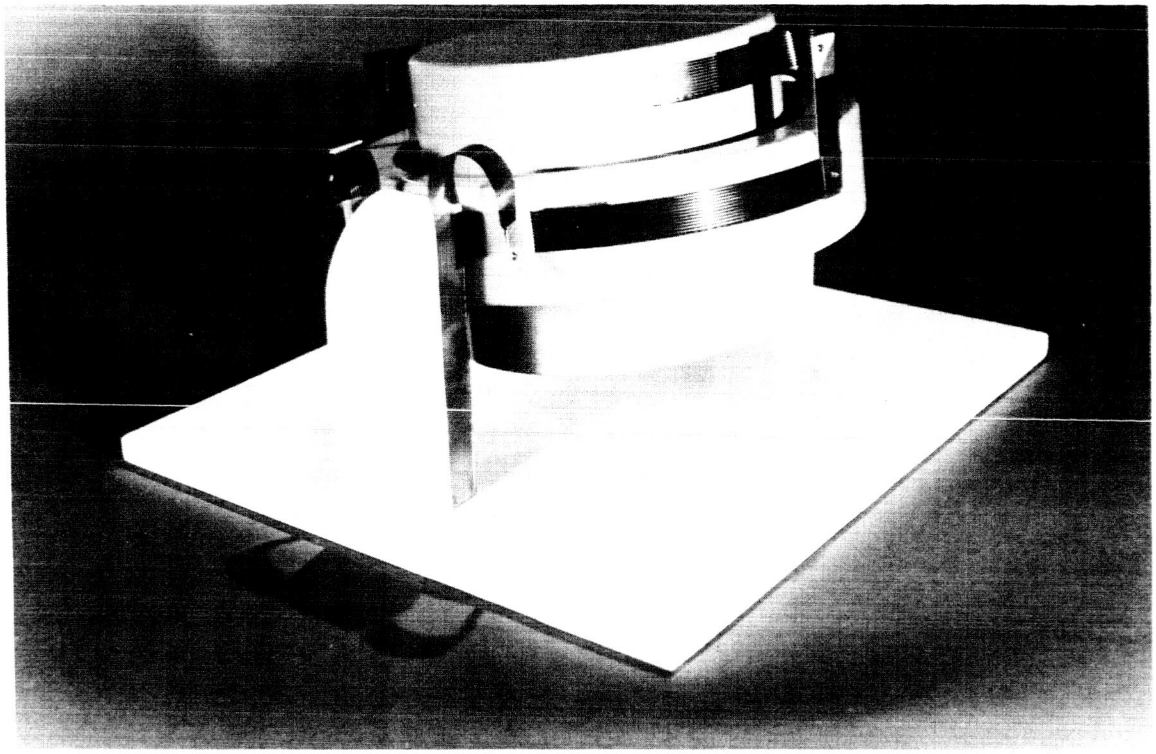


Figure 18. Model depicting general gimbal crossing principle which is being applied to the ATM installation.

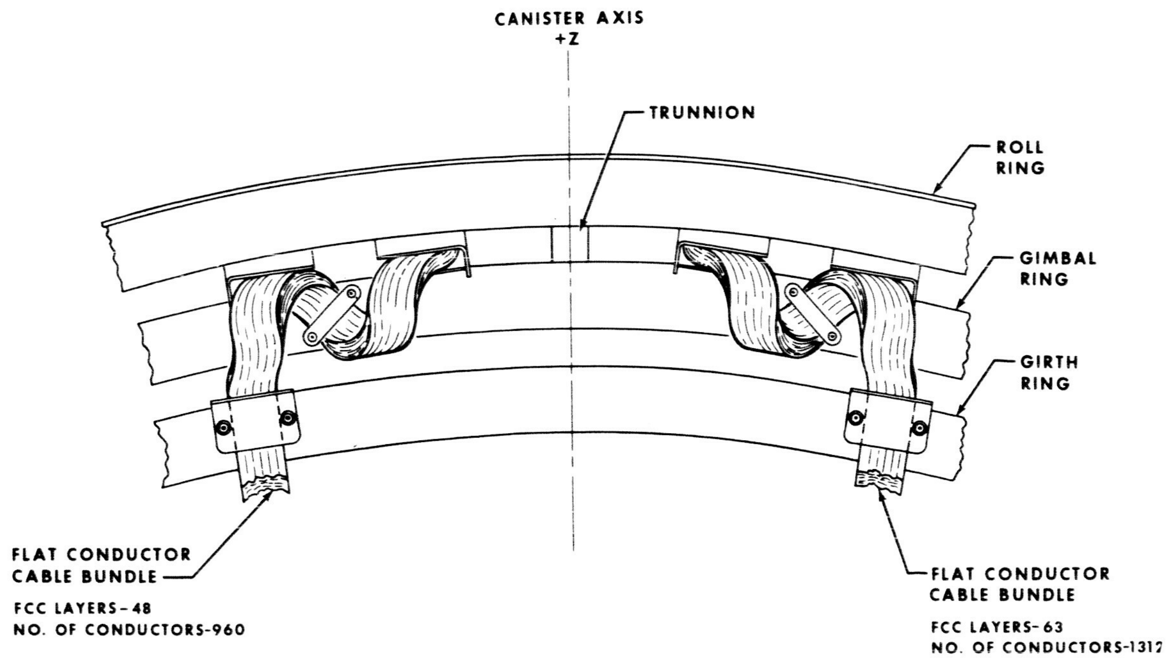


Figure 19. ATM gimbal crossing.

PANEL DISCUSSION

Moderator:

Robert E. Lindstrom---MSFC Shuttle Project Office

Panel Members:

Norman J. Cotter --------- E. I. DuPont

Paul Gamble -------------- Hughes Aircraft

Clyde L. Hatch ------------ U. S. Navy

Richard Schade ------------ Defense Electronic Supply Center

Roger H. Ellis ------------ Raychem

Wilhelm Angele ----------- MSFC Process Engineering Laboratory

Robert A. Klotz ----------- Private Consultant

E. Murray Chalmers ------ Ansley Electronic Corporation

Flat Conductor Cable

Symposium and Hardware Exhibit

October 10-12, 1972

1. QUESTION

WHAT IS FLAT CABLE?

ANSWER

(Angele)

We have heard during these three days of symposium activities, many different names for flat conductor cable. I think we should use a descriptive name for flat conductor cable. It has flat conductors and is a conductor cable. Also, there are many trade names. The trade names are okay, because the companies want to show their own product. But when we talk generally about this cable system, I think we should call it "Flat Conductor Cable," FCC.

2. QUESTION

ARE ANY CABLES BEING QUALIFIED TO MIL-C-55543?

ANSWER

(Schade)

At this time there has been no qualification action completed. We do have two companies that have come in for qualification and we expect them to be qualified to the spec within six months.

3. QUESTION

HOW DO YOU HANDLE FLAT CABLE SHIELDING?

ANSWER

(Gamble)

It depends a great deal of what we expect to shield the cable from or if you expect to shield the internal signals from one another. Flat cable shielding can be handled by perforated or solid metallic surfaces, either layed on as an individual shield as a general ground plane or significantly layed in relation to one or more of the conductors. The shielding may be applied as a vapor deposited metal. It is a very good question, but specific answers to it have to be related to the application for which the cable is made.

(Ellis)

I think that Mr. Gamble is absolutely right. Raychem is relatively new in the flat cable area, primarily because we didn't feel that we had a material that could be used to make flat cable. I think that one of the things that has

happened in industry, which we saw in the survey that we made, is that the cables are becoming complex. And when you start shielding, they become more complex and you have less standardization. If I have anything to preach for Raychem, it's standardization. I think that most of the people who talk about flat cables say something about standardization. One of the things that gets you away from standardization is putting a shield on the cable. We have done considerable planning on the configuration of our cable. It is obviously that you can coat the outside. What we intend to do is to stay standard with the cable and add a piece to it or another strip that goes with it. Because our cables are standard, you can laminate them together and use the top and the bottom as a shield so that you are still able to terminate. I think the big problem with shielding, as we see it, is how do you terminate it once you get it shielded. It is obvious that we can all make cable that has material on the top, but this causes stripping and termination problems; you have a more complex termination. In getting flat cable off the ground, it is certainly our opinion that the number of cables and connectors to be standardized should be kept within practical limits. Part of this standardization has to be in the way that you put a shield on the cable.

(Gamble)

There is another point I would like to make. The decision on the method of shielding is most commonly left up to the manufacturer. I had the privilege of being the designer of the cable which was qualified and eventually used for AEGIS. The specification that was written called out, not the materials, but the dimensions that they were able to put the cables into and the end signals that they wished to have, regardless of the order of the shunt capacitances that were made as this cable was layed out in the final configuration. As a result of that, we gave the manufacturer quite a liberty in his tolerances and the final configuration depends on the opportunity to manufacture with a specific type of material that would give the best effectiveness. It is very important to give that liberty to the manufacturer.

4. QUESTION

WITH REGARD TO THE USE OF FLAT CABLE INSTEAD OF RF COAXIAL CABLE: WHAT IS THE HIGHEST FREQUENCY THAT CAN BE TRANSMITTED WITH ATTENUATION LOSS OF NOT MORE THAN 45 DB PER HUNDRED FEET?

ANSWER

(Chalmers)

On that problem you're replacing coaxial cable. There are generally two reasons for using coaxial cable in the first place. One would be

shielding from the outside world, the other would be the cross talk levels that you would expect to achieve in a high frequency application. For the moment I am going to address myself strictly to the cross talk problem. We have several structures, transmission type cables. In these structures, the construction is quite critical to the natural frequency that you can withstand. Generally speaking, up to 900 megacycles is about the maximum practical limit at those attentuation levels.

5. QUESTION

WITH REGARD TO THE USE OF FLAT CABLE INSTEAD OF RF COAXIAL CABLE: MUST SPECIAL ATTENTION BE PAID TO CONNECTOR DESIGN AND SPLICE DESIGN TO MINIMIZE CHANGE IN CHARACTERISTIC IMPEDANCE AND MAINTAIN LOW VOLTAGE STANDING WAVE RATIO?

ANSWER

(Cotter)

Definitely! If you don't you are going to get into trouble so fast it won't be funny. Obviously you must maintain continuity of connectors to conductors, and maintain the space (shield to the conductor or conductor to conductor).

6. QUESTION

WHY IS IT SIMPLER TO INSTALL FCC THAN ROUND WIRE CABLE?

ANSWER

(Klotz)

Well from the studies that we performed when I was working with Mc Donnell Douglas, the cable (such that you saw on the S-IVB mockup in Building 4711) is modular in nature and lends itself very well to simple stacking which is easy to duplicate. Because of the placement of conductors, the effective shielding has the same effect that you would get from shielding. In general, the bundles are smaller. You can use standard clamps, and studies showed that the reductions in cost, both in mockup development and production installation, showed marked advantages.

(Ellis)

I think one of the differences we see in flat cable is an organized mechanical pattern of wiring. Many people that we have talked to have done their engineering for round cable systems. They would like to use flat cable systems, but they don't have the engineering money to spend. You have to start with a mechanical layout of the wiring system when you

start your initial design; it is very difficult in many cases to try to plug flat cable into a round wire system. But it does something else, at least in our opinion it does something else, it makes the electrical engineer do his job for a change. He now knows where the conductors go. This has to reduce cost, it has to reduce the amount of shielding that you need. So in overall, the whole system is going to be better. I am sure that we have all heard, and I've heard since I've been a young boy, that "when in doubt, shield." With a flat cable system, you can locate where you're circuits go, so you don't have to shield; you shouldn't have to shield. We should be looking at this a lot closer to make sure that shielding is really necessary. With flat cable you have an organized wiring pattern rather than a disorganized pattern. With round wire systems there is a schematic that goes out into the shop and it is left up to the shop people to decide where the wire is located. You never know if it goes to the same place twice. That's not true with flat cable.

7. QUESTION

IS ANY INFORMATION AVAILABLE ON THE RADIATION HARDNESS OF THE NEW RAYCHEM INSULATION MATERIAL?

ANSWER

(Ellis)

Yes, this is the synthesized Raychem material called polyarylene. I cannot give all the answers to the question, but we certainly have data available. I do have some comments. We have run the polyarylene molded parts with a high degree of success in a radiation atmosphere. AECL, which is Atomic Energy Canada Limited, said it was the best plastic they had ever seen. They ran a 2,000 megarad test, and this is gamma radiation. After 1,000 megarads on an electron beam, we ran a wrap and unwrap test on the wire. It turned a light tan color which was expected, but there appeared to be no deterioation of the material at all. We also ran the material at 10^9 rads, in colbalt source, and it still looked good. Tests are being conducted, right now, in these atmospheres. If anybody is interested, we will be glad to give them data. I just don't happen to have very much data with me today.

8. QUESTION

IS THERE ANY SIGNIFICANT CHANGE IN ELECTRICAL PROPERTIES, AS CAPACITANCE, WHEN FCC IS SECURED CONTINUOUSLY VS PERIODIC CLAMPING?

ANSWER

(Cotter)

That is going to depend to some extent upon what the flat conductor cable

is secured to. On this particular question, we aren't sure what the man had in mind, but let's think for a moment. If you ran the cable on the inside of an enclosure or secured to a metal substrate, you have effectively installed a shield for the conductors; you are going to get capacitance coupling to the shield. If on the other hand you had something that was only touching down for a space of 2 inches, every 18 inches or something like that, you aren't going to get much change in terms of total distance. If it's all glued down all the way to a metal, you are going to get a definite change. If the substrate is a nonmetal, you will get none.

(Gamble)

There is another aspect in this I would like to point out. The cable itself, to a great extent, defines the effect of an adjacent ground or some other dissimilar dielectric. The thickness of the dielectric in the cable, the configuration of the wires, and the effect the plate coupling (the capacity coupling which takes place between those flat conductors and the material that acts as the other plate) will have some effect on the capacitance changes and therefore on the impedance of the cables. We have ignored one of the major factors. What if the cable is already shielded? This could be single-side or double-side shielding.

9. QUESTION

ARE THERE ANY FUTURE PROGRAMS IN WHICH THERE IS A GOOD POSSIBILITY OF USING FCC? IF SO, WHAT ARE THEY?

ANSWER

(Hatch)

From my point of view with the Navy, I would say that there are three very good possibilities. One would be for deep submergence vehicles, both rescue and research. Another one is for the equipment modules where the wiring has to be done from the cables running through; for quick turn around time, we would "connectorize" the equipment. Another one is for a new family of ships classified as high performance vehicles of the hydro-foil or air cushion type.

(Schade)

We have found that some of the newer systems for both the Army and the Air Force--and first was the Air Force, with an airborne landing system--have both ground and airborne application of FCC. One of the surprising users was the new T77 Army tank where neither weight, size or cube were real critical, but rather configuration. We found that this was the single largest user of flat conductor cable.

10. QUESTION

PLEASE EXPLAIN THE DIFFERENCE IN COST INFORMATION GIVEN BY MSFC AND BOEING ON FCC HARNESSES?

(Klotz)

We did a little private consulting work last night to try and come up with an unbias answer to that question. Quite obviously I could give you some fancy words, but these fancy words wouldn't do what I'm trying to do in analyzing the problem that we have, which is two different sets of figures. So first of all let's go back to look at the cable that Boeing was talking about. Maybe by getting everything a little closer together we will be able to understand it. They were basically comparing a cable (figure 1) which was 10' long, that had 55 conductors with a round wire connector at one end and branching out into 33 and 22 conductors with round wire connectors at the opposite end. Boeing looked at 8 configurations for this (table 1). I have to go through some of these to give you the background as rapidly as possible. The first one is standard, we know what that is. The second one is small gauge wire with a braided jacket; they went to a small gauge with still the same standard type wire. The third is similar to two except for some convoluted tubing on the back and a higher cost small gauge wire. The fourth, fifth and sixth were very similar, in that they had flat conductor cable, but between the X marks (figure 1) and the connectors, they went through a transition to go back again to the round wire connectors. Seven and eight are what we are really talking about at this symposium for convential, or I should say standard or what ever we want to call it, flat conductor cable systems, where we have flat conductor cable throughout going to rectangular flat conductor cable connectors at either end. Seven, is the AMP Unyt termination connector which is not really environmentally sealed. Eight was using the new ITT Cannon spec connector. Now if you understand that, we can preceed in evaluating the engineering and the operations (which are actually the shop operations), and on the next slide (table 3) you will see what happens when you get into the cost of materials. But at any rate as we look at table 2, and I don't want to take the time to discuss them in detail, you can see that the engineering cost is basically the same for all eight types of cable. These are not my figures, they are Boeings under contract to Manned Space Center. The operations mockup cost is essentially the same for all eight, a little bit higher perhaps for some of the most sophisticated round wire. Remember that number three is really a new program to go to for round wire. The tooling and production planning (table 2) again show not any big differences in cost, except that there is a 100% increase for number three. The fabrication and assembly (table 2) is what is most important to compare. The way we built wire bundles in the past (number one) cost \$3.75 per segment. More sophisticated round wire systems (number three) with

the tape, and the tape the convoluted tubing and all this, costs $4.90 per segment. Number seven, which is the method that we really should use to gain the benefits of flat conductor cable systems, costs $.33 per segment. We know that the AMP Unyt termination system is cut the wire, make the termination, and get it into the connector. So immediately we see, that with the repeatable operations, we are getting somewhat over a 10 to 1 reduction in the cost of fabricating a harness. So the installation cost (table 2) is, again, an improvement for the flat conductor cable by about half the cost, but these costs aren't as much. Now remember, these are not Douglas reports. This is what came from a Boeing report, these figures were taken right out of it. What wasn't obvious to me when I listened to the Boeing report; was what they actually did. When you come to the connector and accessories (table 3), remember numbers one, two, and three are round wire. The cost of connectors and accessories for number one is $46.00. Numbers two and three are for the high performance, very dense round wire with small connectors. The only reason that the cost of wire for number two is less than number one was because Boeing used a smaller gauge, but it was the same spec wire. When they used number three, the improved spec wire for higher performance, the wire cost was $147.00. The reason the cost of wire for numbers seven and eight is a little bit more than numbers five and six is, is because seven and eight are a little bit longer, but seven and eight do not have splices for joining FCC to round wire. This all makes sense as it goes and it says that, basically, flat conductor cable as it cost today is equal to about the same as the improved round wire of tomorrow. This is not contradictory to what McDonnell Douglas, under contract to MSFC, had determined before. But it says, as Mr. Angele has said before, that the basic costs of the material are such that when you start manufacturing and procuring flat conductor cable in very large quantities, you should be able to reduce the cost at least 50% or more. When you look at the cost of the connectors you see something else. You see the cost of the ITT Cannon connector (environmentally sealed) was $270.00 (number eight) versus $184.00 for the improved round wire connector (number three). All that this shows is that we haven't reached minimum FCC connector costs yet. There is some potential cost reduction available with automation and wafer termination. The cost of the FCC connector system must be reduced to where it is equal to or less than the cost of high performance round wire connectors. This is one of the main reasons, and this was also pointed out by Mr. Remedios of Boeing, that the cost was high, and that was because of the connector system. By summarizing these together (table 4), it shows that the difference in total cost (labor and material) of numbers seven or eight is somewhat less than number three, $18.00. Remember that some of the eight cables compared here are not optimum design. Number one is the old fashion type; number two is small gauge wire, but not the improved wire; four, five, and six are "crutches" because we've gone through a transition to utilize existing round wire connectors. Number three is really what we

are looking at, an improved high performance round wire system. Seven and eight are close to what we want. Seven doesn't have an environmentally sealed connector; eight does, but the cost is up because of the cost of the connector. It should come down. The McDonnell Douglas (MDAC) report said, at that time (1968), that there was an approximate 20% savings in material (table 5), 0% on the cable and 40% on the connector. There were the figures that we got after talking to MSFC and other people at that time. We see here on the chart (table 3), that the cables (wire) really didn't help in reducing cost--yet--but we have not done enough home work. We haven't developed what is required. Harness fabrication cost (table 5) was a 80% reduction; the Boeing report showed that it was basically a 90% reduction. From Marshall reports and the quotations we had, materials are up to 72% less if we take into account some of the wire support and clamping hardware. I hope that this has helped bring things back into perspective and to account for the apparent discrepancies.

11. QUESTION

WHAT IS THE AVAILABILITY OF TOOLING TO DEPOTS AND ON SHIPS FOR DOING STRIPPING AND CRIMPING AND EVERY THING ELSE THAT IS REQUIRED FOR REPAIR AND MAINTENANCE OF THE CABLES.

ANSWER

(Hatch)

My answer is to the possible application; we haven't gone into it deep enough to have been tooled-up.

(Angele)

What ever it is, don't repair it. Throw it away and put a new one in.

(Schade)

In-field repair is our greatest concern on FCC; without a doubt, our greatest concern. We must have the capability of the in-field repair. That is one of the reasons we don't have big usages of FCC today.

(Ellis)

That is an interesting question, really. People say, "how do you repair solder?" Well tell me how you are going to put your thumb where your little finger is. That's what flat cable is. What are you going to repair? The things that you can repair, or the things that we have found that you can repair, may be like the damage caused by a guy with a screw driver

in his pocket backing up against the cable and poking a hole into it. You have to come in and fix the one or two cables. But the thinking has to change. You are now talking about a fixed type of thing. What are you going to do when you repair the cable. I think a part of what NASA has tried to do for years is to convery a story that your putting extension cords together, and when you put that extension cord together you're not goint to take the contacts out like you can with 26500 or 5015 or 38300 or all the rest of the connectors that have crimp removable contacts. A different point of thinking has to go into this. This is not going to be successful unless people start thinking that way. Obviously there has to be some repair or some easy way of getting in to fix individual cables where you can jumper them over, but even that can be done with distributor boxes or in the part of the connector it plugs into. But you're not going to fix the termination, you're not going to fix the end of the cable that goes into the NASA connector, you're not going to fix the end of the connector that goes into the Ansley or the Cannon or anybody elses connector. There is no way. Cut it off and throw it away as Mr. Angele has just said. Because you can't shorten one wire and make it shorter than the other, and you can't move it from one side to the other. A is here and Z is here and that's the way it is going to be.

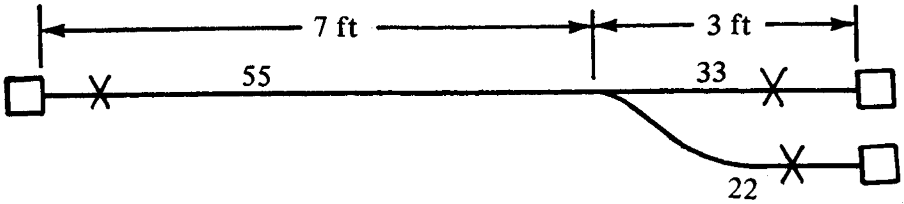


Figure 1.

TABLE 1

(1)	STD RWC Harness
(2)	Small gage wire with braided jacket (RWC)
(3)	Similar to (2) with convoluted tubing last 8 in. (RWC)
(4)	FCC with three Boeing transitions[x] to RWC and round connector.
(5)	Similar to (4) with welded transitions
(6)	Similar to (4) with Raychem MTSM transitions
(7)	FCC with Amp FCC UNYT connectors
(8)	FCC with Cannon 3 wafer Mil-Spec connectors

TABLE 2. LABOR

Task	Cost per Segment ($)							
	1	2	3	4	5	6	7	8
Engineering	3.3	3.6	3.6	3.6	3.5	3.5	3.4	3.4
Operations Mock-up	1.3	1.4	1.5	1.1	1.1	1.0	1.0	1.0
Tool and Prod	.2	.3	.35	.16	.18	.17	.15	.16
Planning								
Fab and Assy	3.75	4.1	4.9	3.1	2.4	3.4	.33	1.14
Installation	1.4	1.6	1.6	1.0	1.0	1.0	.7	.7
	10.0	11.0	12.0	2.9	8.2	9.2	5.56	6.40

TABLE 3. MATERIAL — 30-ft BUNDLE

Part	Assy Cost per Segment ($)*							
	1	2	3	4	5	6	7	8
Conn. & Access.	46	184	184	46 12	46 7	46 18	180	270
Wire	108	89	147	122	122	122	144	144
Total Cost	154	273	331	180	175	186	324	414
Cost Per Segment	2.81	4.94	6.02	3.23	3.16	3.88	5.83	7.50

*$0.87 per segment fixed price.

TABLE 4. TOTAL COST

	1	2	3	4	5	6	7	8
Labor	10.0	11.0	12.0	8.9	8.2	9.2	5.56	6.40
Material	2.8	4.9	6.0	3.3	3.2	3.9	5.83	7.50
Total	12.8	15.9	18.0	12.2	11.4	13.1	11.39	13.90

TABLE 5

NOTE: MDAC Report

Materials 20% sav. (0% Cable, 40% Conn.)
Harness Fab. 80% sav.

MSFC Report

Materials + 72%

HARDWARE EXHIBITORS

Allied Chemical Corporation
Plastics Division
P. O. Box 2365 R
Morristown, N.J. 07960

AMP Incorporated
P. O. Box 3608
Harrisburg, Penn. 17105

Ansley Electronics Corporation
Old Easton Road
Doylestown, Penn. 18901

Berg Electronics, Inc.
Route 83 Expressway
New Cumberland, Penn. 17070

Burndy Corporation
Richards Avenue
Norwalk, Conn. 06852

Hobby Hill, Inc.
417 N. State Street
Chicago, Ill. 60610

Hughes Aircraft Co.
Connecting Devices Division
500 Superior Avenue
Newport Beach, Calif. 92663

ITT Cannon Electric Company
2801 Airlane Street
Phoenix, Ariz. 85034

Kings Electronics Company, Inc.
40 Marblehead Road
Tuckahoe, N.Y. 10707

North American Rockwell Corp.
12214 Lakewood Blvd.
Downey, Calif. 90241

Parlex Corporation
145 Milk Street
Metheun, Mass. 01844

Raychem Corporation
300 Constitution Drive
Menlo Park, Calif. 94025

Southern Weaving Company
Woven Electronics Division
P. O. Box 189
Mauldin, S.C. 29662

Switchpack Systems, Inc.
P. O. Box 670
Del Marr, Calif. 92014

The Boeing Company
P. O. Box 3707
Seattle, Wash. 98124

LIST OF ATTENDEES

Mr. David J. MacFadyen
ABT Associates, Inc.
55 Wheeler St.
Cambridge, Mass. 02138

Mr. Loyd Hill
ADC Products
4900 West 78th St.
Minneapolis, Minn. 55435

Mr. Garry Griffin
Advanced Tech. Corp.
P.O. Box 5205
Huntsville, Ala. 35805

Dr. A. B. Robertson
Allied Chemical
Plastic Div.
P.O. Box 2365R, Bldg. DAB
Morristown, N. J. 07960

Mr. J. E. Wilkinson
Amphenol/Bunker Ramo
3131 S. Dixie Dr.
Dayton, Ohio 45439

Mr. T. G. Elliott
Amphenol Industrial Div.
Bunker Ramo Corp.
1830 S. 54th Ave.
Chicago, Ill. 60650

Mr. Carl Occhipinti
Amphenol Industrial Div.
Bunker Ramo Corp.
1830 S. 54th Ave.
Chicago, Ill. 60650

Mr. Fred B. Keiter
Ampine
2220 Park Lane Dr.
Atlanta, Ga.

Mr. David V. Benfer, Manager
AMP Inc.
P.O. Box 3608
Harrisburg, Pa. 17105

Mr. J. F. Martz
AMP Inc.
P. O. Box 3608
Harrisburg, Pa. 17105

Mr. R. J. O'Neill
AMP Inc.
P.O. Box 3608
Harrisburg, Pa. 17105

Dr. J. J. Redslob
AMP Inc.
P.O. Box 3608
Harrisburg, Pa. 17105

Mr. Tom Rybicki
AMP Inc.
6018 Village Glen
Dallas, Tex.

Mr. E. M. Chalmers
Ansley Elec. Corp.
Old Easton Rd.
Doylestown, Pa. 18901

Mr. John Churchill
Ansley Elec. Corp.
Old Easton Rd.
Doylestown, Pa. 18901

LIST OF ATTENDEES (Continued)

Mr. Wm. A. Uline
Astro-Space Lab. Inc.
110 Wynn Dr. N.W.
Huntsville, Ala. 35806

Mr. K. W. Heimendinger
Automon Systems, Inc.
1314-B Buford St.
Huntsville, Ala. 35810

Mr. R. B. Wysor
Automon Systems, Inc.
1314-B Buford St.
Huntsville, Ala. 35810

Mr. Ian Brown
Bell Helicopter Co.
P.O. Box 482
Fort Worth, Tex. 76101

Mr. Jack DeVries
Bell Telephone Labs.
Rm. 5A 114
Whippany Rd.
Whippany, N. J. 07981

Mr. G. A. Cripps
Bendix Aerospace Sys. Div.
3300 Plymouth Rd.
Ann Arbor, Mich. 48107

Mr. Hal M. Avery
Bendix Corp.
Elec. Comp. Div.
Sherman Ave.
Sidney, N. Y. 13838

Mr. J. C. Cole
Bendix Corp.
Elec. Comp. Div.
Sherman Ave.
Sidney, N. Y. 13838

Mr. David A. Luzadis
Bendix Corp.
Elec. Comp. Div.
Sherman Ave.
Sidney, N. Y. 13838

Mr. D. E. Michel
Bendix Corp.
Sherman Ave.
Sidney, N. Y. 13838

Dr. Seong K. Rhee
Bendix Corp.
Elec. Comp. Div.
Sherman Ave.
Sidney, N. Y. 13838

Mr. Gerald C. Smith
Bendix Corp.
Elec. Comp. Div.
Sherman Ave.
Sidney, N. Y. 13838

Mr. Lloyd Wingfield
Berg Electronics
4951 N.E. 28th Ave.
Light House Point, Fla. 33064

Mr. Richard Petersen
Berg Electronics
Route 83 Expressway
New Cumberland, Pa. 17070

LIST OF ATTENDEES (Continued)

Mr. Irving E. Cope
The Boeing Co.
Org. 5-9416
Mail Stop J.C. 40
P.O. Box 1470
Huntsville, Ala. 35802

Mr. Gresh Downs
The Boeing Co.
P.O. Box 1470
Huntsville, Ala. 35807

Mr. Don Nalley
The Boeing Co.
P.O. Box 1470
Huntsville, Ala. 35807

Mr. Terry Purtle
The Boeing Co.
P.O. Box 1470
Huntsville, Ala. 35807

Mr. David H. Moss
The Boeing Co.
H.S.-02
P.O. Box 58747
Houston, Tex. 77058

Mr. D.W. Fitzwater
The Boeing Co.
Mail Stop LS-85
P.O. Box 29100
New Orleans, La. 70129

Mr. H. L. Ernst
The Boeing Co.
Mail Stop 47-18
P.O. Box 3707
Seattle, Wash. 98124

Mr. M. D'Almada Remedios
The Boeing Co.
Commercial Airplane Elec. Sys.
Mail Stop 47-18
P.O. Box 3707
Seattle, Wash. 98124

Mr. John J. Andiarid
Boeing Vertol
Philadelphia, Pa.

Mr. D. L. Cumbaa
Brandel-Stephen & Co.
11311 S. Memorial Parkway
Huntsville, Ala. 35803

Mr. George Graeber
Brand-Rex Co.
Willimantic, Conn. 06226

Mr. John Smith
Brand-Rex Co.
Willimantic, Conn. 06226

Mr. B Green
Buchanan Elec. Prod. Corp.
4425 Bandini Blvd.
Los Angeles, Calif. 90023

Mr. R. P. Aldighieri
Buchanan Elec. Prod. Corp.
1065 Floral Ave.
Union, N. J. 07083

Mr. Bill Waddington
Buchanan Elec. Prod. Corp.
1065 Floral Ave.
Union, N. J. 07083

LIST OF ATTENDEES (Continued)

Mr. J. Cameron
Bunker Ramo Corp.
Amphenol Connector Div.
2801 S. 25th Ave.
Broadview, Ill. 60153

Mr. Henry L. Burr
Burndy Corp.
Richards Ave.
Norwalk, Conn. 06852

Mr. Henry Dupre
Burndy Corp.
Richards Ave.
Norwalk, Conn. 06852

Mr. Jon Wigby
Burndy Corp.
Richards Ave.
Norwalk, Conn. 06852

Mr. Eugene Hawkins
Celesco Industries
3333 Harbor Blvd.
Costa Mesa, Calif. 92626

Mr. R. J. Bork
Chrysler Corp.
Space Div.
P.O. Box 29200
New Orleans, La. 70129

Mr. Amel Deshautreaux
Chrysler Corp.
Space Div.
P.O. Box 29200
New Orleans, La. 70129

Mr. J. F. Tibolla
Circle F. Industries
P.O. Box 591
Trenton, N. J. 08604

Mr. Forrest Kramer
Collins Radio Co.
Bldg. 106-187
5200 C. Ave. N
Cedar Rapids, Iowa 52406

Mr. Sam Langham
Control Data Corp.
West Lake Village, Calif.

Mr. Leon Gilbert
Continental Connector Corp.
34-63 56th St.
Woodside, N. Y. 11377

Mr. Guy Palmquist
Continental Connector Corp.
34-63 56th St.
Woodside, N. Y. 11377

Mr. R. Schade
DESC-EMT
Defense Elec. Supply Ctr.
Dayton, Ohio 45444

Mr. Henry Cameau
The Deutsch Co.
Municipal Airport
Banning, Calif. 92220

Mr. Roland Lawrence
The Deutsch Co.
7001 West Imperial Highway
Los Angeles, Calif. 90045

LIST OF ATTENDEES (Continued)

Mr. Willard S. Ziekafoose
The Deutsch Co.
135 Candace Dr.
Matland, Fla.

Mr. J. L. Bowen
E. F. Johnson Co.
299 10th Ave. S.W.
Waseca, Minn. 56093

Dr. R. G. Brown
E. I. Dupont de Nemours & Co.
Plastics Dept.
1007 Market St.
Wilmington, Del. 19898

Mr. N. J. Colter
E. I. Dupont de Nemours & Co.
Plastics Dept. Tech. Serv. Lab.
1007 Market St.
Wilmington, Del. 19898

Mr. R. T. Lovell
E. I. Dupont de Nemours & Co.
Plastics Dept.
1007 Market St.
Wilmington, Del. 19898

Mr. Lloyd E. Mackall
E. I. Dupont de Nemours & Co.
1007 Market St.
Wilmington, Del. 19898

Mr. J. W. Dehart, Jr.
E. I. Dupont de Nemours & Co.
Film Dept.
Chestnut Run
Wilmington, Del. 19898

Mr. C. E. Baker
Elco Corp.
Maryland Rd. & Computer Ave.
Willow Grove, Pa. 19090

Mr. A. J. Hyland
Elco Co.
Maryland Rd. & Computer Ave.
Willow Grove, Pa. 19090

Dr. A. P. Belle Isle
G.D./Ordnance Sys.
100 Plastics Ave.
WCCE-Rm. 2556
Pittsfield, Mass. 01201

Mr. R. W. Lauben
General Electric Co.
41 Woodford Ave.
Plainville, Conn. 06062

Mr. J. I. Smith
General Electric Co.
41 Woodford Ave.
Plainville, Conn. 06062

Mr. Carroll F. Kane
General Electric Co.
100 Plastics Ave.
Pittsfield, Mass. 01201

Mr. Clayton Baucher
General Electric Co.
AESD Dept.
French Rd.
Utica, N. Y. 13503

LIST OF ATTENDEES (Continued)

Mr. R. J. Pawlick
General Electric Co.
AESD Dept
Mail Drop 211
French Rd.
Utica, N. Y. 13503

Mr. J. C. Thomson
General Electric Co.
Mail Drop 215
French Rd.
Utica, N. Y. 13502

Mr. E. F. Caulson
General Electric Co.
P.O. Box 8661, Rm. 2644
Philadelphia, Pa. 19101

Mr. Richard Pietroski
General Electric Co.
P.O. Box 8555, Rm. 2112U
Philadelphia, Pa. 19101

Mr. A. C. Risko
General Electric Go.
Rm 4000
3198 Chestnut St.
Philadelphia, Pa. 19421

Mr. R. C. Cressman
General Electric Co.
95 Hathaway St.
Providence, R. I. 02902

Mr. Richard Bradshaw
Grumman Aerospace Corp.
Dept. 544 Plant 35
Bethpage, N. Y. 11714

Mr. Richard E. Johnson
GTE Sylvania
816 Lexington Ave.
Warren, Pa. 16365

Mr. A. Righini
GTE Sylvania
77A St.
Needham, Mass. 02194

Mr. Bill Hand
Hayes International Corp.
204 Oakwood Ave. N.E.
Huntsville, Ala. 35807

Mr. D. F. Jackson
Hayes International Corp.
PEL Operations
Huntsville, Ala.

Ms. C. Swanson
Hayes International Corp.
204 Oakwood Ave. N.E.
Huntsville, Ala. 35807

Mr. Leo Wolf, President
Hobby Hill, Inc.
417 North State Street
Chicago, Ill. 60610

Mr. B. A. Gerpheide
Hughes Aircraft Co.
Bldg. 6, Mail Stop D-133
Teale St.
Culver City, Calif. 90230

Mr. Clyde J. Deverell
Hughes Aircraft Co.
El Segundo, Calif.

LIST OF ATTENDEES (Continued)

Mr. D. Cianciulli
Hughes Aircraft Co.
Conn. Devices Oper.
500 Superior Ave.
Newport Beach, Calif. 92663

Mr. Paul Gamble
Hughes Aircraft Co.
Mail Stop C-1410
500 Superior Ave.
Newport Beach, Calif. 92663

Mr. Wayne S. Burton
Hurst Mfg. Corp.
Princeton, Ind. 47570

Mr. Lou Osman
ITT Cannon Elec.
P.O. Box 20803
2801 Air Lane
Phoenix, Ariz. 85036

Mr. Thomas M. Hooper
ITT Federal Elec. Co.
2109 Clinton St.
Huntsville, Ala. 35805

Mr. M. M. Woodbury
ITT Federal Elec. Co.
2109 Clinton St.
Huntsville, Ala. 35805

Dr. Yiu Sing Liu
John C. Calhoun State Tech.
Jr. College
32 Woodside Dr.
Route 7
Athens, Ala. 35611

Mr. E. D. Corcoran
Kings Federal Elec. Co.
40 Marbledale Rd.
Tuckahoe, N. Y. 10707

Mr. Fred Della Iacono
Kings Federal Elec. Co.
40 Marbledale Rd.
Tuckahoe, N. Y. 10707

Mr. F. J. Hines
Langley Research Center
NASA Mail Stop 351
Bldg. 647
Hampton, Va. 23365

Mr. J. D. Perdue
Langley Research Center
NASA Mail Stop 159
Langley St.
Hampton, Va. 23365

Mr. Lee A. Seymour, Jr.
L. Frank Markel & Sons
1959 School Lane
Norristown, Pa. 19494

Mr. W. J. Barnett
McDonnell Douglas Astron. Co.
5301 Bolsa. Ave.
Huntington Beach, Calif. 92647

Mr. Jack Holmes
McDonnell Douglas Astron. Co.
AEA2 Mail Sta. 13-3
5301 Bolsa Ave.
Huntington Beach, Calif. 92647

LIST OF ATTENDEES (Continued)

Mr. R. P. Fialcowitz
McDonnell Douglas Astron. Co.
Mail Stop 36-43
3855 Lakewood Blvd.
Long Beach, Calif. 90801

Mr. G. R. Salisbury
McDonnell Douglas Astron. Co.
P. O. Box 516
St. Louis, Mo. 63166

Mr. Ronald S. Soloman
McDonnell Douglas Astron. Co.
Dept. 354, Bldg. 33N
P. O. Box 516
St. Louis, Mo. 63166

Mr. Paul E. Fitzgerald, Jr.
Manned Spacecraft Center
AT
Houston, Tex. 77058

Mr. Phil Moran
Manned Spacecraft Center
ND53
Houston, Tex. 77058

Attendees from Marshall Space Flight Center, Alabama 35812

Mr. W. C. Fersch
A&PS-PR-RD

Mr. A. K. Rockefeller
A&PS-PR-RD

Mr. Marvin H. Brown
A&PS-TU-DIR

Mr. James W. Wiggins
A&PS-TU-DIR

Mr. W. A. Mrazek
PD-DIR

Mr. Harry I. Thayer
S&E-ASTN-ESD

Mr. Buford E. Gallaher
S&E-ASTR

Mr. H. W. Kampmeier
S&E-ASTR-B

Mr. F. B. Moore
S&E-ASTR-DIR

Mr. Robert M. Aden
S&E-ASTR-E

Mr. James W. Glass
S&E-ASTR-EA

Mr. Bill McPeak
S&E-ASTR-EBC

LIST OF ATTENDEES (Continued)

Mr. Charles H. Southern
S&E-ASTR-EBC

Mr. Ernst Lange
S&E-ASTR-MS

Mr. W. L. Howard
S&E-ASTR-SE

Mr. D. J. Ackerman
S&E-ASTR-SEA

Mr. Wilhelm Angele
S&E-PE-M

Mr. Vincent P. Caruso
S&E-PE-M

Mr. Ray E. Van Orden
S&E-PE-M

Mr. J D Bennight
S&E-PE-ME

Mr. James D. Hankins
S&E-PE-ME

Mr. John R. Rasquin
S&E-PE-ME

Mr. Robert M. Avery
S&E-PE-MEE

Mr. Hubert E. Smith
S&E-PE-MEE

Mr. M. J. Whittington
S&E-PE-MEE

Mr. Roy Taylor
S&E-PE-MEI

Mr. W. A. Wall
S&E-PE-MEI

Mr. L. C. Jackson
S&E-PE-MEP

Mr. James R. Carden
S&E-PE-MES

Mr. C. C. Corum
S&E-PE-MES

Mr. Ralph H. Herndon
S&E-PE-MES

Mr. Warren Kelly
S&E-PE-MES

Mr. R. W. Loggins
S&E-PE-MES

Mr. James P. McLemore
S&E-PE-MES

Mr. W. E. Norton
S&E-PE-MES

Mr. James M. Willis
S&E-PE-MES

Dr. Bill N. Bhat
S&E-PE-MX

Mr. James P. Bates
S&E-QUAL-A

LIST OF ATTENDEES (Continued)

Mr. R. M. Henritze
S&E-QUAL-A

Mr. John M. Knadler III
S&E-QUAL-AR

Mr. W. M. Barden
S&E-QUAL-QP

Mr. Quentin C. Soprano
S&E-QUAL-QP

Mr. Dennis E. Thrasher
S&E-QUAL-QP

Mr. Henry Rickett
S&E-QUAL-QPB

Mr. Lew Burdette
S&E-QUAL-QT

Mr. Bill Corder
S&E-QUAL-QT

Mr. M. F. Nowakowski
S&E-QUAL-QT

Mr. Frank Hall
Martin Marietta Corp.
P. O. Box 179
Denver, Colo. 80201

Mr. Wm. T. Perreault
Martin Marietta Corp.
Mail Stop SO453
P. O. Box 179
Denver, Colo. 80201

Mr. R. F. Wells
Martin Marietta Corp.
Mail Stop SO455
P. O. Box 179
Denver, Colo. 80201

Mr. Robert Novak
Martin Marietta Corp.
Mail Point 297
Orlando, Fla. 32800

Mr. R. H. Murphy
The Wiremold Co.
West Hartford, Conn. 06110

Mr. E. A. Ross
Woven Elec.
Div. of Southern Weaving
P. O. Box 189
Mauldin, S.C. 29662

Mr. D. R. Coleman
Wyommissing Corp.
Narrow Fabric Div.
7th & Reading Ave.
Reading, Pa. 19603

Mr. Dennis Wilson
Xerox Corp.
701 S. Aviation
Mail Stop A2-30
El Segundo, Calif. 90205

LIST OF ATTENDEES (Continued)

Mr. Charles Wiltgen
Methode Electric Co.
7447 W. Wilson Ave.
Chicago, Ill. 60656

Mr. Irving B. Levine
Micro Cable Co.
Div. of Parlex Corp.
145 Milk St.
Methuen, Mass. 01844

Mr. Robert M. Doherty
Microdot Inc.
220 Pasadena Ave.
S. Pasadena, Calif. 91030

Dr. Robert F. Carlton
Middle Tenn. State Univ.
P.O. Box 407
Murfreesboro, Tenn. 37130

Mr. L. E. O'Rourke
Mobay Chemical Co.
Penn. Lincoln Parkway West
Pittsburgh, Pa. 15205

Mr. Thomas Berilla
National Security Agency
Bldg. 3, Rm. S-212
Fort Meade, Md. 20755

Mr. Howard Ireland
Naval Air Div. Center
AVTD, BTYE
Warminster, Pa. 18971

Mr. Ronald Richardson
Naval Air Systems
Command Air 533541
Washington, D.C.

Mr. C. Buman
Naval Elec. Lab. Center
San Diego, Calif. 92152

Mr. T. H. Hamm
Naval Elec. Lab. Center
San Diego, Calif. 92152

Mr. Clyde L. Hatch
Naval Ship. Engr. Center
3700 East-West Highway
Hyattsville, Md. 20782

Mr. Michael De Lucia
Naval Ship R&D Center
Code 2772
Annapolis, Md. 21402

Mr. Vaughn Goodin
North American Rockwell Corp.
3322 S. Memorial Parkway
Huntsville, Ala. 35801

Mr. Jim D. Dayle
North American Rockwell Corp.
Space Div. SE-82
12214 Lakewood Blvd.
Downey, Calif. 90241

Mr. John Hammons
North American Rockwell Corp.
12214 Lakewood Blvd.
Downey, Calif. 90241

Mr. W. F. Iceland
North American Rockwell Corp.
Space Div. 41-070
Mail Code AE24
12214 Lakewood Blvd.
Downey, Calif. 90241

LIST OF ATTENDEES (Continued)

Mr. Wm. L. Malohn
North American Rockwell Corp.
12214 Lakewood Blvd.
Downey, Calif. 90241

Mr. G. K. Romriell
North American Rockwell Corp.
Space Div. 41-153
Mail Code AA91
12214 Lakewood Blvd.
Downey, Calif. 90241

Mr. James Vandergriff
North American Rockwell Corp.
12214 Lakewood Blvd.
Downey, Calif. 90241

Mr. James L. Crouse
Packard Elec. GMC
Warren, Ohio

Mr. Herbert W. Pollack
Parlex Corp.
145 Milk St.
Methuen, Mass. 01844

Mr. Marian Surat
Parlex Corp.
144 Milk St.
Methuen, Mass. 01844

Mr. Alf H. Johnsen
Picatinny Arsenal
NDB300 Bldg. 95
Dover, N. J. 07801

Mr. Robert F. Van Ness
Picatinny Arsenal
U.S. Army NWD Bldg. 95
Dover, N. J. 07801

Mr. R. A. Klotz
Pine Villa Estates
203 Woodland Route #3
Post Falls, Idaho 83854

Mr. Victor M. Barr
Raychem Corp.
300 Constitution Dr.
Menlo Park, Calif. 94025

Mr. Wm. A. Berry
Raychem Corp.
300 Constitution Dr.
Menlo Park, Calif. 94025

Mr. Raj S. Cornelius
Raychem Corp.
300 Constitution Dr.
Menlo Park, Calif. 94025

Mr. Roger H. Ellis
Raychem Corp.
300 Constitution Dr.
Menlo Park, Calif. 94025

Mr. Thomas H. McGrewey
Raychem Corp.
300 Constitution Dr.
Menlo Park, Calif. 94025

Mr. Robert M. Neel
Raychem Corp.
300 Constitution Dr.
Menlo Park, Calif. 94025

Mr. W. Robinson
Raychem Corp.
300 Constitution Dr.
Menlo Park, Calif. 94025

LIST OF ATTENDEES (Continued)

Mr. Robert Simpson
Raychem Corp.
7040 Lake Ellenor Dr.
Orlando, Fla. 32809

Mr. William Burkhart
Raychem Corp.
Atlanta, Ga.

Mr. G. Sunderland
Raychem Corp.
Dix Hill, N. Y.

Mr. Bruce R. Carson
Raytheon Co.
Hartwell Rd.
Bedford, Mass. 01730

Mr. I. Holliday
Raytheon Co.
Wayland, Mass. 01778

Mr. Donald R. Hood
Raytheon Co.
Wayland, Mass. 01778

Mr. Rua Raymond
Raytheon Co.
P.O. Box 360
Portsmouth, R. I. 02871

Mr. James F. Simon
Raytheon Co.
Internal Box 125
P.O. Box 360
Portsmouth, R. I. 02871

Mr. Irving D. Kruger
RCA Missile & Surface Radar Div.
Bldg. 101-203
Morrestown, N. J. 08057

Mr. M. Bellard
Sikorsky Aircraft Div.
United Aircraft/ACSS
Stratford, Conn. 06602

Mr. Arnold Peters
Singer-Eng. Prec. Inc.
Librascope Sys. Div.
808 Western Ave.
Glendale, Calif. 91201

Mr. Edward F. Finn
South Eastern Assoc.
2400 Clinton Ave. West
Huntsville, Ala. 35805

Mr. Alan S. Hintze
Space Nuclear Sys. Off.
U.S. Atomic Com.
Washington, D.C. 20545

Mr. James H. Donnelly
Spaco Inc.
Huntsville, Ala. 35805

Mr. Stewart Ebnetter
Spaceo Inc.
Huntsville, Ala. 35805

Mr. Frank J. Hales
Sperry Rand Corp.
Huntsville, Ala.

Mr. Peter Marchiony
Sperry Rand Corp.
Huntsville, Ala. 35805

Mr. R. D. Pyle
Teledyne Kinetics
410 S. Cedros
Solana Beach, Calif. 92075

LIST OF ATTENDEES (Continued)

Mr. D. Dombrowsky
Tensolite Insulated Wire Co.
198 Main St.
Tarrytown, N. Y. 10591

Mr. Ralph Harlow
Tensolite Insulated Wire Co.
198 W. Main St.
Tarrytown, N. Y. 10591

Mr. Howard C. Litt
Thermo Resist Inc.
2430 Cypress Way
Fullerton, Calif.

Mr. Robert Ruiz
Thermo Resist Inc.
2430 Cypress Way
Fullerton, Calif.

Mr. V. F. Dahlgreen
TME Corp.
Salem Industrial Park
Salem, N. H. 03079

Mr. C. W. Hille
TRW Systems
One Space Park
Redondo Beach, Calif. 90278

Mr. R. Salcedo
TRW Systems
One Space Park
Redondo Beach, Calif. 90278

Mr. James V. Byrd
U.S. AMICOM
Bldg. 4500
AMSMI-QC-RSA
Huntsville, Ala. 35809

Mr. Dan Lichtenstein
U.S. Army Electronics Command
AMSEL-TL-NE
Ft. Monmouth, N. J. 07703

Mr. L. R. Wright
U.S. Army Missile Command
AMSMI-RCS
Redstone Arsenal, Ala. 35809

Mr. Wm. D. Varner
SAFLOG
U.S. Army SAFEGUARD
AMSSI-RLT
P.O. Box 2400
Wynn Dr.
Huntsville, Ala. 35805

Mr. H. H. Hasselbring
U.S. Naval Avionics Facility
21st St. & Arlington Ave.
Indianapolis, Ind. 46210

Mr. Thomas E. Alves
U.S. Naval Ordnance Station
Advanced Tech. Br.
Code 5043/MDS 33
Louisville, Ky. 40214

Mr. Wm. G. Jenkins
U.S. Naval Ordnance Station
Code 50234
Southside Dr.
Louisville, Ky. 40214

Mr. J. W. Balde
Western Electric Co., Inc.
P.O. Box 900
Princeton, N. J.

LIST OF ATTENDEES (Concluded)

Mr. Bill Johnson
Zippertubing Co.
13000 S. Broadway
Los Angeles, Calif. 90061

Mr. Joe Bizon
220 Parklane Dr.
N. Lake Mall
Atlanta, Ga. 30305

Mr. Larry Pruitt
6415 Chadwell Rd.
Huntsville, Ala. 35802

APPROVAL

FLAT CONDUCTOR CABLE SYMPOSIUM, OCTOBER 10-12, 1972

By James D. Hankins (Coordinator)

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This document has also been reviewed and approved for technical accuracy.

W. Angele

W. ANGELE
Chief, Research and Process Technology Division

11/1/73

M. P. L. SIEBEL
Director, Process Engineering Laboratory

DISTRIBUTION

INTERNAL

DIR
DEP-T

A&PS-PAT
Mr. L. D. Wofford, Jr.

A&PS-MS-H
A&PS-MS-IP (2)
A&PS-MS-IL (8)
A&PS-TU (6)

A&PS-PR-RD
Mr. W. C. Fersch
Mr. A. K. Rockefeller

A&PS-TU-DIR
Mr. Marvin H. Brown
Mr. James W. Wiggins

PD-DIR
Mr. W. A. Mrazek

S&E-ASTN-ESD
Mr. Harry I. Thayer

S&E-ASTR
Mr. Buford E. Gallaher

S&E-ASTR-B
Mr. H. W. Kumpmeier

S&E-ASTR-DIR
Mr. F. B. Moore

S&E-ASTR-E
Mr. Robert M. Aden

S&E-ASTR-EA
Mr. James W. Glass

S&E-ASTR-EBC
Mr. Bill McPeak
Mr. Charles H. Southern

S&E-ASTR-MS
Mr. Ernst Lange

S&E-ASTR-SE
Mr. W. L. Howard

S&E-ASTR-SEA
Mr. D. J. Ackerman

S&E-PE-M
Mr. Wilhelm Angele
Mr. Vincent P. Caruso
Mr. Ray E. Van Orden

S&E-PE-ME
Mr. J D Bennignt
Mr. James D. Hankins (100)
Mr. John R. Rasquin

S&E-PE-MEE
Mr. Robert M Avery
Mr. Hubert E. Smith
Mr. M. J. Whittington

S&E-PE-MEI
Mr. Roy Taylor
Mr. W. A. Wall

S&E-PE-MEP
Mr. L. C. Jackson

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Minneapolis, Minn. 55435
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Attn: Dr. A. B. Robertson

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Dayton, Ohio 45439
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2801 S. 25th Ave.
Broadview, Ill. 60153
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Bunker Ramo Corp.
1830 S. 54th Ave.
Chicago, Ill. 60650
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Harrisburg, Pa. 17105
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Huntsville, Ala. 35801
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P.O. Box 482
Fort Worth, Tex. 76101
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Whippany Rd.
Whippany, N. J. 07981
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3300 Plymouth Rd.
Ann Arbor, Mich. 48107
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Elec. Comp. Div.
Sherman Ave.
Sidney, N. Y. 13838
Attn: Mr. Hal M. Avery
Mr. J. C. Cole
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Route 83 Expressway
New Cumberland, Pa. 17070
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Mr. Paul Fitting
Mr. Richard Petersen

Berg Electronics
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Light House Point, Fla. 33064
Attn: Mr. Lloyd Wingfield

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Huntsville, Ala. 35807
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P.O. Box 29100
New Orleans, La. 70129
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H. S.-02
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Houston, Tex. 77058
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Los Angeles, Calif. 90023
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Union, N. J. 07083
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Broadview, Ill. 60153
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Norwalk, Conn. 06852
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3333 Harbor Blvd.
Costa Mesa, Calif. 92626
Attn: Mr. Eugene Hawkins

Chrysler Corp.
Space Div.
P.O. Box 29200
New Orleans, La. 70129
Attn: Mr. R. J. Bork
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Cinch-Grapik
Div. of TRW
200 S. Turnbull Canyon Rd.
City of Industry, Calif. 91744
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Cinch Mfg.
Div. of TRW
1500 Morse Ave.
Elk Grove Village, Ill. 60007
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1007 Market St.
Wilmington, Del. 19898
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Souderton, Pa. 18964
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5901 S. County Rd. 18
Minneapolis, Minn. 55436
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Republic Aviation Div.
71 Holiday Office Center
Huntsville, Ala. 35800
Attn: Mr. Carver T. Bussey

G. D./Ordnance Sys.
WCCE-Rm. 2556
100 Plastics Ave.
Pittsfield, Mass. 01201
Attn: Dr. A. P. Belle Isle

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41 Woodford Ave.
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General Electric Co.
100 Plastics Ave.
Pittsfield, Mass. 01201
Attn: Mr. Carrol F. Kane

General Electric Co.
P.O. Box 43
Schenectady, N. Y. 12301
Attn: Mr. John Harnden, Jr.

General Electric Co.
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Syracuse, N. Y. 13201
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Utica, N. Y. 13503
Attn: Mr. Chas. C. Pace, Jr.

General Electric Co.
AESD Dept.
French Rd.
Utica, N. Y. 13503
Attn: Mr. Clayton Baucher
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General Electric Co.
P.O. Box 8661
Philadelphia, Pa. 19101
Attn: Mr. E. F. Coulson (Rm 2644)

General Electric Co.
Space Div.
P.O. Box 8555
Philadelphia, Pa. 19101
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Hicksville, N. Y. 11802
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2001 S. St., N.W.
Washington, D.C. 20009
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1211 Air Way
Glendale, Calif. 91201
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Goddard Space Flight Center
Code 713
Greenbelt, Md. 20771
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GTE Sylvania
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Hampton, Va. 23365
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Pittsburgh, Pa. 15205
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Washington. D.C. 20390
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Hyattsville, Md. 20782
Attn: Mr. Clyde L. Hatch

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Code 2772
Annapolis, Md. 21402
Attn: Mr. Michael De Lucia

North American Rockwell Corp.
3322 S. Memorial Parkway
Huntsville, Ala. 35801
Attn: Mr. Vaughn Goodwin

North American Rockwell Corp.
12214 Lakewood Blvd.
Downey, Calif. 90241
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North American Rockwell Corp.
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Los Angeles, Calif. 90009
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North American Rockwell Corp.
Dept. 059-095-AD27
International Airport
Los Angeles, Calif. 90009
Atnn: Mr. G. Waddy

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NASA
Washington, D.C. 20546
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Attn: Mr. J. B. Lopez

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Dover, N. J. 07801
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Huntsville, Ala. 35805
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Bldg. 101-203
Morrestown, N. J. 08057
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Box 368
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United Aircraft/ACSS
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Glendale, Calif. 91201
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2400 W. Clinton Ave.
Huntsville, Ala. 35805
Attn: Mr. Edward F. Finn

Space Nuclear Sys. Office
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Washington, D.C. 20545
Attn: Mr. Alan S. Hintze

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Tarrytown, N. Y. 10591
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Flushing, N. Y. 11354
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Fullerton, Calif.
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Salem, N. H. 03079
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TRW Systems
One Space Park
Redondo Beach, Calif. 90278
Attn: Mr. C. W. Hille
Mr. R. Salcedo

Torpedo Wire & Strip Inc.
Torpedo Rd. 2
Pittsfield, Pa. 16340
Attn: Mr. Robert N. Underhill

University of Ala.
Res. Inst.
P.O. Box 1247
Huntsville, Ala. 35807
Attn: Mr. David Christensen

USAF
Dept. MMEAE
McClevand AFB, Calif. 95652
Attn: Mr. H. W. King

U.S. AMICOM
Bldg. 4500
AMSI-QC-RSA
Huntsville, Ala. 35809
Attn: Mr. James V. Byrd

U.S. Army Electronics Command
AMSEL-TL-NE
Ft. Monmouth, N. J. 07703
Attn: Mr. Dan Lichtenstein

U.S. Army Missile Command
ANSMI-RGP-Bldg. 7421
Redstone Arsenal, Ala. 35809
Attn: Mr. Loyd L. Woodham

U.S. Army Missile Command
AMSMI-RCS
Redstone Arsenal, Ala. 35809
Attn: Mr. L. R. Wright

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U.S. Army SAFEGUARD
AMSSI-RLI
P.O. Box 2400
Wynn Dr.
Huntsville, Ala. 35805
Attn: Mr. Wm. D. Varner

U.S. Naval Avionics Facility
21st St. & Arlington Ave.
Indianapolis, Ind. 46210
Attn: Mr. H. H. Hasselbring

U.S. Naval Ordnance Station
Advanced Tech. Br.
Code 5043/MDS 33
Louisville, Ky. 40214
Attn: Mr. Thomas E. Alves

U.S. Naval Ordnance Station
Code 50234
Southside Dr.
Louisville, K. 40214
Attn: Mr. Wm. G. Jenkins

U.S. Steel Homes
2549 Charles Town Rd.
New Albany, Ind. 47150
Attn: Mr. Bruce M. Duncan

Varian Assoc.
D-161
611 Hansen Way
Palo Alto, Calif. 94304
Attn: Mr. J. G. Dallinger

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Dept. 3823
Burlington, N. C.
Attn: Mr. R. P. Hickey

Western Electric Co., Inc.
Dept. 3654
204 Graham Hopedale Rd.
Greensboro, N. C.

Western Electric Co., Inc.
Dept. 318120
801 Merritt Dr.
Greensboro, N. C. 27407
Attn: Mr. Fred N. Talley

Western Electric Co., Inc.
Dept. 7482
2400 Reynolda Rd.
Winston-Salem, N. C. 27102
Attn: Mr. C. J. Testo

Western Electric Co., Inc.
P.O. Box 900
Princeton, N.J.
Attn: Mr. Hans Ammann
Mr. J. W. Balde

Westinghouse Elec. Corp.
P.O. Box 746
Baltimore, Md. 21203
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Mr. O. A. Lin Ciniero (M/S 292)
Mr. Charles A. Harper (M/S 496)
Mr. J. J. Henderson

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Res. & Engr. Center
Benton Harbor, Mich. 49022
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West Hartford, Conn. 06110
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Div. of Southern Weaving
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7th & Reading Ave.
Reading, Pa. 19603
Attn: Mr. D. R. Coleman

Xerox Corp.
701 S. Aviation
Mail Stop A2-30
El Segundo, Calif. 90205
Attn: Mr. Dennis Wilson

Zippertubing Co.
13000 S. Broadway
Los Angeles, Calif. 90061
Attn: Mr. Bill Johnson

220 Parklane Dr.
North Lake Mall
Atlanta, Ga. 30305
Attn: Mr. Joe Bizar

6415 Chadwell Rd.
Huntsville, Ala. 35802
Attn: Mr. Larry Pruitt

152 W. 42nd St.
New York, N. Y. 10036
Attn: Mr. Lewis Winner